

I 19.3:1383-D

88-298

✓

VOLCANICLASTIC SEDIMENTATION IN THE LEWIS RIVER VALLEY, MOUNT ST. HELENS, WASHINGTON— PROCESSES, EXTENT, AND HAZARDS

RECEIVED
MAY 18 1988

Darius Library
Winthrop College
Documents Department



U.S. GEOLOGICAL SURVEY BULLETIN 1383-D

COVER

Aerial view of Mount St. Helens and Spirit Lake from the northeast (compare with similar view on covers of Bulletins 1383A–C). Catastrophic debris avalanche and ensuing eruption on 18 May 1980 removed a vast portion of the volcano and created the large horseshoe-shaped crater. A widespread lateral blast removed almost all vegetation on nearby slopes north of the mountain and knocked down trees on slopes farther out (lower left). Large destructive lahars that formed within minutes of the onset of the eruption swept down the east and west flanks of the volcano. Photograph taken on 24 July 1980 by Austin Post.

Volcaniclastic Sedimentation in the Lewis River Valley, Mount St. Helens, Washington— Processes, Extent, and Hazards

By JON J. MAJOR *and* KEVIN M. SCOTT

GEOLOGY OF MOUNT ST. HELENS VOLCANO, WASHINGTON

U.S. GEOLOGICAL SURVEY BULLETIN 1383-D



UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1988

DEPARTMENT OF THE INTERIOR
DONALD PAUL HODEL, *Secretary*

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, *Director*

Library of Congress Cataloging-in-Publication Data

Major, Jon J.

Volcaniclastic sedimentation in the Lewis River valley, Mount St. Helens,
Washington.

(Geology of Mount St. Helens Volcano, Washington)

U.S. Geological Survey Bulletin 1383-D

Supt. of Docs. No.: I 19.3:1383-D

Bibliography.

1. Volcanic ash, tuff, etc.—Washington (State)—Lewis River Watershed. 2.
Sedimentation and deposition—Washington (State)—Lewis River Watershed. 3.
Saint Helens, Mount (Wash.) I. Scott, Kevin M., 1935— . II. Series. III.
Series: U.S. Geological Survey Bulletin 1383-D.

QE75.B9 No. 1383-D
[QE461]

557.3s
[552'.23'0979784]

87-600008

CONTENTS

	Page
Abstract - - - - -	D1
Introduction - - - - -	2
Terminology - - - - -	4
Acknowledgments - - - - -	5
Eruptive history of Mount St. Helens - - - - -	6
Description of deposits - - - - -	6
Swift Reservoir - - - - -	6
Swift Dam to Yale Lake - - - - -	8
Older Swift Creek assemblage - - - - -	8
Younger Swift Creek assemblage - - - - -	10
Yale Lake area - - - - -	11
Yale Dam to Lake Merwin - - - - -	13
Speelyai Valley and Lake Merwin - - - - -	19
Downstream from Merwin Dam - - - - -	23
Flood-plain age and development in the lower Lewis River valley - - - - -	24
Lahar and debris-avalanche hazards in the Lewis River valley - - - - -	28
Present eruptive period - - - - -	28
Future eruptive periods - - - - -	30
Debris avalanches - - - - -	30
Lahars - - - - -	33
Future eruptive periodicity - - - - -	35
References cited - - - - -	35

ILLUSTRATIONS

	Page
FIGURE 1. Map showing location of river systems draining Mount St. Helens - - - - -	D3
2-10. Photographs showing:	
2. Aerial view of Lewis River valley looking upstream near Swift Dam - - - - -	8
3. Granular lahar overlain by runout-flow deposits along the eastern shore of Yale Lake - - - - -	12

	Page
FIGURE 4. Megaclast of stratified alluvium incorporated in lake-breakout-type lahar near Yale Dam and megaclast of poorly sorted debris-avalanche deposit incorporated in lake-breakout-type lahar near Yale Dam - - - - -	D14
5. Lahar overlain by transition-facies deposits in borrow pit north of State Highway 503 bridge over Lewis River - - -	17
6. Younger slope-mantling lahars unconformably overlying older section of lahars in roadcut near State Highway 503 bridge over Lewis River - - - - -	18
7. Runout-flow, lahar, and alluvial deposits in a gravel pit in the bay of Speelyai Creek - - - - -	20
8. Cobble-rich flood-surge-type lahar exposed near the mouth of Jim Creek - - - - -	22
9. Slope-mantling lahar deposit exposed below Merwin Dam - -	23
10. Transition-facies deposit exposed about 1 kilometer downstream from Merwin Dam - - - - -	25

TABLES

	Page
TABLE 1. Summary of eruptive periods of Mount St. Helens - - - - -	D7
2. Summary of radiocarbon dates of volcanoclastic deposits in the Lewis River valley - - - - -	9

CONVERSION FACTORS

For the convenience of readers who prefer to use inch-pound units rather than the metric (International System) units used in this report, the following conversion factors are provided:

Multiply metric unit	By	To obtain inch-pound unit
centimeter (cm)	0.394	inch (in.)
meter (m)	3.281	foot (ft)
cubic meter (m ³)	35.287	cubic foot (ft ³)
kilometer (km)	0.621	mile (mi)
cubic kilometer (km ³)	0.239	cubic mile (mi ³)
cubic meter per second (m ³ /s)	35.287	cubic foot per second (ft ³ /s)

Sea level: In this report “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called “Mean Sea Level of 1929.”

**VOLCANICLASTIC SEDIMENTATION
IN THE LEWIS RIVER VALLEY,
MOUNT ST. HELENS, WASHINGTON—
PROCESSES, EXTENT, AND HAZARDS**

By JON J. MAJOR and KEVIN M. SCOTT

ABSTRACT

During its approximately 50,000 year history, Mount St. Helens episodically has contributed large volumes of granular volcaniclastic sediment into the Lewis River valley and its tributaries. Although much of this sediment resulted in thick valley fill near the volcano, lahars (volcanic debris flows) did travel long distances down the Lewis River valley. Deposits of large lahars coat valley walls at least 50 km (kilometers) downstream from the volcano to heights of more than 30 m (meters) above the present valley floor. Similar slope-mantling deposits (dated at $3,920 \pm 365$ radiocarbon years) have been identified at a distance of 35 km from the volcano. These deposits clearly indicate that valley-filling lahars from relatively recent eruptive periods traveled long distances down the Lewis River valley. Paleohydrologic analyses suggest that these flows had discharges of more than $100,000 \text{ m}^3/\text{s}$ (cubic meters per second).

Flow transformation has been an important sedimentologic process in the Lewis River valley. Downstream from Mount St. Helens, lahars generally transformed from dense, high-strength debris flows to less-sediment-rich runout flows (hyperconcentrated stream-flow evolved from a distal lahar). Beyond 50 km, the transformations of lahars from Mount St. Helens accelerated in response to valley widening. Consequently, sedimentation at the mouth of the Lewis River valley was dominated by fluvial processes. The process of flow transformation in the downstream decay of lahars in the Lewis River valley also was influenced by the noncohesive nature of the lahars (less than 2 percent clay). Many lahars in the valley probably did not originate as fully developed mass flowage on the slopes of the mountain, but rather as water surges or underdeveloped lahars that bulked by erosion of stream alluvium from the tributary valleys draining the mountain.

Because the crater of Mount St. Helens now faces north, lahars are unlikely to affect the southerly draining Lewis River valley during the present eruptive period, unless large-scale explosive activity resumes or the location of the vent changes. If lahars generated as a direct result of an eruption threaten Swift Reservoir, they probably will not exceed a volume of 170 million m^3 (cubic meters).

Although lahars constitute a potential hazard to the Lewis River valley, the constraining design event during a future eruptive period is a debris avalanche. Studies conducted since 1980 indicate that debris avalanches have occurred several times in the volcano's brief history. A debris avalanche of even one-half the size of that of 1980 would probably have devastating consequences if it were to occur in the Lewis River drainage basin.

INTRODUCTION

Volcanogeomorphic processes observed and inferred at Mount St. Helens since the paroxysmal 1980 eruption have provided considerable insight into the modes of origin and transport of volcanoclastic debris. Lahars (volcanic debris flows) precipitated by the eruptions of 1980–82 were generated in several ways: (1) by slumping and flowage of water-saturated portions of the debris-avalanche deposit, which caused the volumetrically largest and most devastating flow in the North Fork Toutle River (Janda and others, 1981); (2) by catastrophic ejection of wet debris that was transformed (Fisher, 1983) into dense, flowing masses (Janda and others, 1981; Scott, 1985a,b; Major and Voight, 1986; Scott and Janda, 1987); and (3) by pyroclastic material melting and mixing with snow and ice (Janda and others, 1981; Pierson, 1985; Fairchild, 1987; Major and Newhall, 1987; Brantley and Waitt, in press; R.B. Waitt, oral commun., 1987). Small eruptions since 1980 have generated floods of water that have traveled beyond the crater, eroded large amounts of loose sediment, and transformed into lahars that flowed down the Toutle River valley. For example, an explosive dome-building event in March 1982 generated a lahar that traveled down the Toutle River valley (Waitt and others, 1983) and became progressively diluted with streamflow (Scott, 1985b; Pierson and Scott, 1985). As a result, coarse particles settled out and this flow underwent a downstream transformation from a coarse, high-strength lahar to a less-sediment-rich, finer grained hyperconcentrated streamflow known as runout flow (Scott, 1985b; Pierson and Scott, 1985).

Recognition of the process of flow transformation allowed Scott (1985b, 1986) to identify and date more than 30 prehistoric Mount St. Helens lahar deposits in the Toutle River valley (fig. 1). One of Scott's most significant findings was the recognition of several lahar deposits that resulted not directly from eruptions of Mount St. Helens, but from erosion of massive amounts of unconsolidated deposits by flood surges that resulted from the breaching of naturally dammed lakes during the Pine Creek eruptive period (3,000 to 2,500 radiocarbon years ago). One such deposit represents the largest lahar known from Mount St. Helens; the flow that produced this deposit had an estimated instantaneous peak discharge of 200,000 to 300,000 m³/s as far away as 50 km from the volcano (Scott, 1986, in press) and was equivalent to the Amazon River at flood stage, or 10 to 15 times the mean annual discharge at the mouth of the Mississippi River.

An understanding of the magnitude and frequency of past lahars in the Toutle River system permitted an improved estimate over past studies (Crandell and Mullineaux, 1978) of the potential hazards associated with lahars from future eruptions of Mount St. Helens. Scott

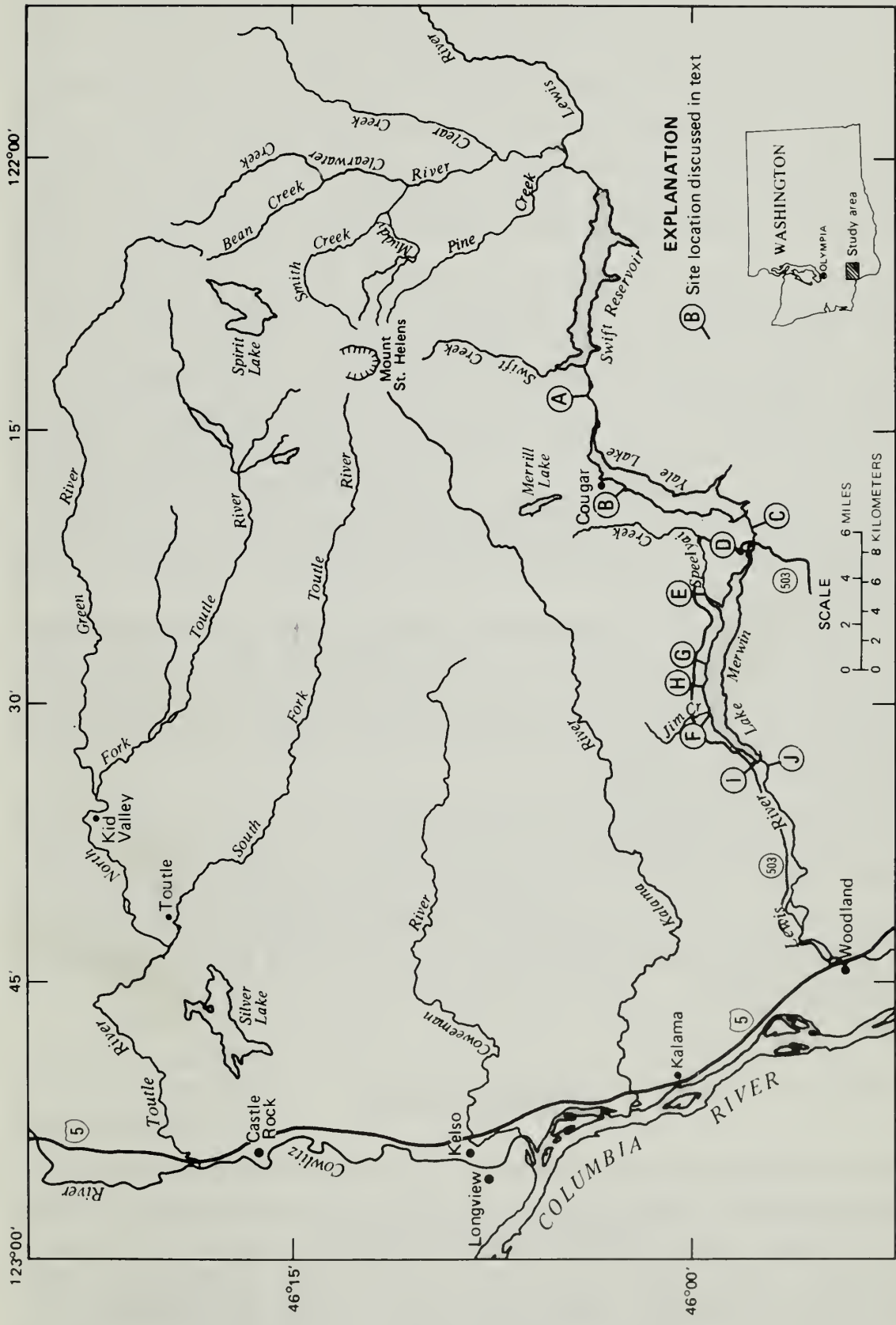


FIGURE 1.—Location of river systems draining Mount St. Helens. Letters refer to locations discussed in text.

and others (1986) have concluded that the Toutle River is an example of a volcanoclastic fluvial system in which potential hazards can be better assessed from a design lahar rather than from a design flood.

In comparison with the Toutle River watershed, the magnitude and frequency of lahars in the Lewis River system, which drains the south and east flanks of Mount St. Helens (fig. 1), are not well known. In a study of volcanoclastic deposits on the south flank of Mount St. Helens, Hyde (1975) recognized two stratigraphic sequences of lahars, pyroclastic flows, and associated alluvium, which he called the older and younger parts of the Swift Creek assemblage. The older part of the Swift Creek assemblage is bracketed by radiocarbon dates of about 36,000 and 18,000 years, and the younger part of the Swift Creek assemblage is about 13,000 radiocarbon years old (Hyde, 1975). Subsequent to the 1980 eruptions, Mullineaux and Crandell (1981) and Newhall (1982) examined several of these deposits and concluded that a debris avalanche may have occurred during the later stages of emplacement of the older part of the Swift Creek assemblage. Newhall concluded that the debris avalanche probably dammed the Lewis River, and that later breaching of the dam generated a large lahar similar to the largest lahars recognized in the Toutle River system by Scott (1985b, 1986, in press).

This report presents the results of a stratigraphic and sedimentologic study conducted in 1985–86 in the Lewis River valley, mostly downstream from Swift Reservoir. The aim of this study was to reinterpret and extend the stratigraphic record of lahars and to reassess potential hazards from future lahars.

Three lakes impounded for hydroelectric power on the Lewis River (fig. 1) limit most exposures to areas between the lakes and the dams. However, while lake levels were drawn down to accommodate seasonal filling, shorelines were examined to look for additional exposures, as were streambank exposures along the lower Lewis River downstream from Merwin Dam.

TERMINOLOGY

The term lahar is used in this report to refer to the mass flowage of water-saturated volcanic debris, as well as the subsequent deposits. This definition mainly follows previous usage of the term (Crandell, 1971; Hyde, 1975; Janda and others, 1981; Pierson, 1985; Scott, 1985b, 1986; Major and Voight, 1986). This type of mass flow generally consists of not less than 80 percent sediment by weight (Beverage and Culbertson, 1964; Pierson and Scott, 1985), although some investigators have used threshold concentrations as low as 70 percent

(Osterkamp and others, 1986). The debris incorporated in these flows may be either hot or cold, but generally it is cold.

Debris avalanche refers to the process of mass wastage of parts of the volcano by large landslides that quickly develop into rock-fragment flows. Commonly, the failed rock mass develops into a rockslide—the rapid downward and outward movement of the rock mass along one or several surfaces or relatively narrow zones (Voight and others, 1981, 1983). Disaggregation of the rock mass can then cause the movement to take on the character of a flow. At Mount St. Helens, this process has been referred to as rockslide-avalanche (Voight and others, 1981, 1983) and rockslide-debris avalanche (Glicken, 1986). We use the term debris avalanche for brevity.

Pyroclastic flow refers to the flow of hot, dry, fragmental volcanic debris. Unlike a lahar, whose fluid medium is water, the fluid medium of a pyroclastic flow generally is heated air and other gases. Pyroclastic flows may be composed of either pumiceous or lithic material, and they may be generated in several different ways (see Chapin and Elston, 1979, and references therein).

The term runout flow refers to a sediment-rich flow, generally devoid of coarse gravel, that is characterized by hyperconcentrated streamflow containing 40 to 80 percent sediment by weight (Beverage and Culbertson, 1964; Scott, 1985b; Pierson and Scott, 1985). This type of flow results from the progressive dilution of a lahar with overrun streamflow and the concomitant loss of coarse sediment. Runout flows thus evolve from lahars, and the presence of the deposit produced by such a flow generally implies an associated lahar somewhere upstream. All traceable deposits of hyperconcentrated streamflows in the Toutle and Lewis Rivers are the distal equivalents of lahars, but this need not be uniformly the case, and exceptions probably occur at other volcanoes less productive of volcaniclastic debris.

Tephra refers to explosively ejected fragmental volcanic debris transported through the air and deposited as fallout. Tephra deposits may be composed of pumiceous fragments (magmatic material), lithic fragments (pieces of older rock), or some combination. For a more complete discussion of tephra, the reader is referred to Fisher and Schmincke (1984).

ACKNOWLEDGMENTS

We thank many of our Geological Survey colleagues for stimulating discussion and helpful reviews during the course of our field work and report preparation. In particular, we thank D.R. Crandell, W.R. Osterkamp, C.D. Miller, R.J. Janda, and J.H. Hyde for their careful,

thought-provoking critiques of this report, and D.R. Mullineaux for his assistance in identifying pumice fragments in the field. We also thank D.F. Meyer, P.T. Pringle, and Jack Kleinman for their boating skills and assistance during the course of the field work.

ERUPTIVE HISTORY OF MOUNT ST. HELENS

Since Verhoogen (1937) demonstrated that Mount St. Helens is a youthful cone overlying an older volcanic complex, the history of this volcano has been studied in detail (Mullineaux and Crandell, 1962, 1981; Hopson, 1971; Crandell and Mullineaux, 1973, 1978; Hyde, 1975; Hoblitt and others, 1980; Mullineaux, 1986; D.R. Crandell, written commun., 1986) and has been divided into a series of eruptive periods (Hoblitt and others, 1980; Crandell and others, 1981; Mullineaux and Crandell, 1981). Each period is defined by eruptive activity that was associated in time, and the periods are separated by dormant intervals inferred chiefly from buried soils and the lack of identifiable eruptive products (Mullineaux and Crandell, 1981; Mullineaux, 1986). Until about 2,500 years ago, Mount St. Helens apparently erupted only dacite and silicic andesite, and these rocks have come to be known as the old Mount St. Helens lithologies (Verhoogen, 1937). After about 2,500 years ago, the mountain began to erupt mafic andesite and basalt in addition to silicic andesite and dacite (Hoblitt and others, 1980; Mullineaux and Crandell, 1981). Known eruptive periods of Mount St. Helens, their approximate ages, and the major tephra units associated with each period are summarized in table 1.

DESCRIPTION OF DEPOSITS

SWIFT RESERVOIR

Eruptions from the old Mount St. Helens volcanic center sent flows of volcanoclastic debris into the Lewis River valley via Pine Creek, Muddy River, and Swift Creek (fig. 1). Near the upper end of Swift Reservoir, Crandell and Mullineaux (1973) identified three sequences of deposits: (1) The oldest sequence consists of the deposits of lithic pyroclastic flows and lahars that are younger than the S tephra set and older than the J tephra set. These deposits belong to the Swift Creek eruptive period (table 1; Mullineaux and Crandell, 1981; Mullineaux, 1986). (2) A sequence of pyroclastic-flow, lahar, and alluvial deposits younger than tephra set J but older than tephra set Y has been recognized near the mouth of Pine Creek. Based on soil development

at the top of this sequence, Crandell and Mullineaux (1973) suggested that it was probably closer in age to set J than to set Y. (3) The most extensive and best preserved deposits are younger than tephra set Y but older than tephra set B. Close to the mountain, this sequence consists primarily of pyroclastic-flow deposits having individual units as much as 15 m thick. At a distance of about 11 km from the base of the cone, lahars begin to predominate, and they compose most of the fill observed near the head of Swift Reservoir (Crandell and Mullineaux, 1973).

TABLE 1.—*Summary of eruptive periods of Mount St. Helens*

[Modified from Mullineaux and Crandell, 1981; Mullineaux, 1986]

Eruptive period	Approximate age	Associated tephra unit
Goat Rocks	180 - 123 yr before 1980	T
Kalama	500 - 350 yr before 1980	X W
Sugar Bowl	¹ 1,200	D
Castle Creek	2,200 - 1,700	B
Pine Creek	3,000 - 2,500	P
Smith Creek	4,000 - 3,300	Y
Swift Creek	13,700 - 9,200	J S
Cougar	20,400 - 18,200	K M
Ape Canyon	40,000 to 50,000 - <36,000	C

¹Age of this and older eruptive periods in radiocarbon years before 1950.

Few deposits are exposed along the shores of Swift Reservoir, except at its east end and near Swift Dam. Some deposits are preserved along the southeastern shore of the reservoir. Most of those deposits are fine- and coarse-grained lahars containing older Mount St. Helens dacites and andesites. Individual flow units range in thickness from about 1 to 7 m and are interbedded with alluvium and sandy runout-flow deposits. All of the deposits observed are capped by well-developed soil zones as much as 2 m thick, indicating that they are at least as old as the Swift Creek eruptive period, and probably older (table 1).

SWIFT DAM TO YALE LAKE

Near Swift Dam at the mouth of Swift Creek, volcanoclastic deposits form a fan more than 150 m thick (fig. 2). The deposits composing this fan were ascribed by Hyde (1975) to the Swift Creek assemblage, which he divided into older and younger parts.

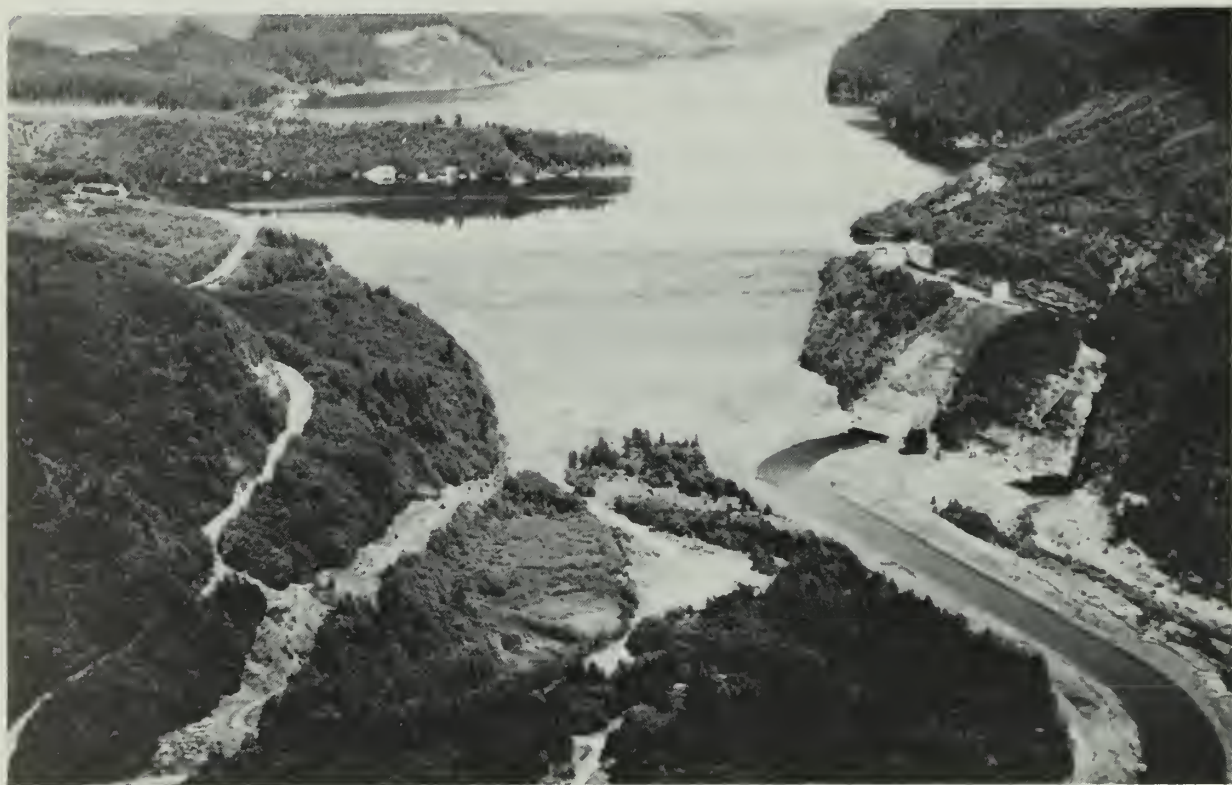


FIGURE 2.—Aerial view of Lewis River valley looking upstream near Swift Dam. The thick Swift Creek assemblage (Hyde, 1975) forms the valley fill on the left side of the photograph (traversed by road). Swift Reservoir is in the background (compare with figure 3 of Hyde, 1975).

OLDER SWIFT CREEK ASSEMBLAGE

The oldest exposed part of the assemblage crops out on the valley bottom between Swift Dam and Yale Lake (location A, fig. 1). In the SE $\frac{1}{4}$ sec. 30, T. 7 N., R. 5 E., a lahar is exposed in the right bank of the Lewis River. This deposit, about 1 m of which is exposed, is weathered and indurated. It has an average clast size of about 1 to 2 cm but contains clasts as large as 30 cm. Although the composition of the clasts is predominantly older Mount St. Helens dacites and silicic andesites, a few are of a white, biotite-bearing pumice. Noncarbonized wood fragments are abundant in this deposit. Hyde (1975) reported a

radiocarbon date of about 36,000 years, and wood that we collected has been dated as greater than 35,800 radiocarbon years (table 2). This deposit thus represents a lahar from the Ape Canyon eruptive period, the earliest known period of activity of Mount St. Helens. The base of the deposit is not exposed; however, drilling logs (cited in Hyde, 1975) indicate angular rock fragments, pumice, and wood down to a depth of 49 m below the present river level. Although it is not known whether these holes penetrated one or several texturally similar deposits, these data indicate that the Lewis River was flowing at a level locally about 50 m lower in altitude when Mount St. Helens came into existence (Hyde, 1975).

TABLE 2.—*Summary of radiocarbon dates, in years, of volcanoclastic deposits in the Lewis River valley*

Date	Material	Reference
440 \pm 70	Wood from alluvial section near Woodland	This study
695 \pm 340	Wood from alluvial section near Woodland	This study
3,920 \pm 365	Composite wood sample from lahar veneer deposit near State Highway 503 bridge	This study
13,130 \pm 350	Charcoal from pyroclastic flow near mouth of Swift Creek	Hyde (1975)
13,415 \pm 310	Charcoal from top of lahar in pit near State Highway 503 bridge	This study
18,560 \pm 550	Charcoal from pyroclastic flow on south side of Lewis River	Hyde (1975)
20,350 \pm 500	Charcoal from pyroclastic flow on south side of Lewis River	Hyde (1975)
22,720 \pm 1400	Charcoal from alluvial sediments below lahar	This study
>35,800	Wood from valley-bottom lahar near Swift Dam	This study
36,000 \pm 2,000	Wood from valley-bottom lahar near Swift Dam	Hyde (1975)

The section of fluvial gravels, pyroclastic flows, and lahars overlying the valley-bottom fill is described by Hyde (1975). Of particular note is a borrow-pit exposure on the south side of the Lewis River valley about 1.5 km west of Swift Dam. In this borrow pit, which exposes a section near the top of a huge volcanoclastic fan, lies a coarse, clast-rich flowage deposit of unknown origin overlain by pyroclastic flow deposits, fluvial gravels, and a tephra couplet (Hyde, 1975). Radiocarbon dates of charcoal samples from the pyroclastic flow deposits, which bracket the tephra couplet, yielded ages of $20,350 \pm 500$ and $18,560 \pm 550$ radiocarbon years. The radiocarbon dates indicate that those events occurred during the Cougar eruptive period (table 1).

Since the 18 May 1980 eruption of Mount St. Helens, the coarse flowage deposit described by Hyde (1975) has generated particular interest. On the north side of the Lewis River valley near Swift Dam, this deposit, which is as much as 20 m thick, contains angular biotite-bearing clasts in a compact silty-sand matrix. Locally, this deposit contains texturally similar megaclasts, several meters in diameter, of pink, hydrothermally altered dacite similar to that exposed in the modern crater. Mullineaux and Crandell (1981) and Newhall (1982) have proposed that this deposit may represent an ancient analog of the 18 May 1980 debris avalanche. It is possible, however, that the megaclasts were eroded from a debris avalanche closer to the volcano and that the deposit enclosing these megaclasts in the Lewis River valley represents a lahar generated from the debris avalanche. The biotite-bearing clasts, presumed to be products of the Ape Canyon eruptive period because similar lithologies have not been identified in products of the Cougar eruptive period, indicate that the avalanche probably was derived from the oldest parts of the ancestral cone (Mullineaux and Crandell, 1981; Newhall, 1982). Hyde (1975), Mullineaux and Crandell (1981), and Newhall (1982) have correlated the flowage deposit underneath the pyroclastic-flow deposits on the south side of the Lewis River valley with the possible debris-avalanche deposit on the north side of the valley. Whether the coarse flowage deposit is a debris avalanche or a lahar containing megaclasts of a debris avalanche, it nonetheless represents an extremely large flow that reached the Lewis River valley and may have dammed the Lewis River during an early part of the Cougar eruptive period (Newhall, 1982).

YOUNGER SWIFT CREEK ASSEMBLAGE

In the Swift Creek valley about 4 km north of Swift Reservoir, deposits of the younger part of the Swift Creek assemblage overlie till of the Fraser glaciation (Hyde, 1975; D.R. Crandell, written commun.,

1986). On the east valley wall near the mouth of Swift Creek, Hyde (1975) observed that a younger section of pyroclastic flow and lahar deposits, overlain by tephra set S, rests upon units of the older part of the Swift Creek assemblage. Charcoal from a pyroclastic flow deposit in that younger section yielded a date of $13,130 \pm 350$ radiocarbon years (Hyde, 1975).

On the south side of the Lewis River valley about 1 km downstream from Swift Dam, a terrace composed of multiple flowage deposits is probably inset against the older part of the Swift Creek assemblage. The oldest deposit exposed in this terrace is a lahar containing angular, pebble-sized clasts of older Mount St. Helens lithologies. This deposit exhibits normal grading of only the coarser particles, from pebbles to coarse sand and granules, over a thickness of 4 m. Downsection, the deposit is covered, but a small window in the vegetation suggests that its lower part may contain subangular clasts several centimeters in diameter, and that the deposit may be more than 10 m thick.

The basal lahar is separated from an overlying lahar by about 0.5 m of coarse, pebbly alluvium and by a runout-flow deposit. The younger lahar, which is about 3 m thick, contains subangular to subrounded clasts as large as 20 cm and is inversely graded over its basal 20 to 25 cm. Again, clast composition is exclusively older Mount St. Helens dacites and andesites.

Capping this suite of deposits is a third, very coarse-grained lahar that is separated from the older lahars by a 2-m-thick section of pumice-rich gravelly sand alluvium. Clasts in this youngest lahar are also composed of the older Mount St. Helens lithologies. The clasts generally are subangular to subrounded and are as large as 1.5 m across. On top of this unit there is a well developed soil zone.

The top of this suite of deposits forms a flat topographic surface at an altitude of 225 m. Although the mineralogic composition of the pumiceous material in these deposits is similar to that of tephra older than tephra set S (D.R. Mullineaux, oral commun., 1986), lack of evidence of erosion, such as fluvial reworking at the top of this sequence, suggests that the terrace is a depositional, rather than an erosional, feature. Although the deposits apparently are younger than the older part of the Swift Creek assemblage, their precise age is uncertain.

YALE LAKE AREA

Along the shores of Yale Lake, lahar and runout-flow deposits are exposed at lake level at several localities, commonly underlying alluvium as thick as 10 m. The runout-flow deposits are typically less than 1 m thick and consist of a poorly sorted mix of coarse lithic sand

and granules of older Mount St. Helens lithic lithologies (fig. 3). The lahars typically are very poorly sorted, and most clasts in them are less than 10 cm in diameter. The clasts are generally angular to subangular and are composed of older Mount St. Helens lithologies. Exposures of lahars generally are less than 2 m thick (fig. 3).

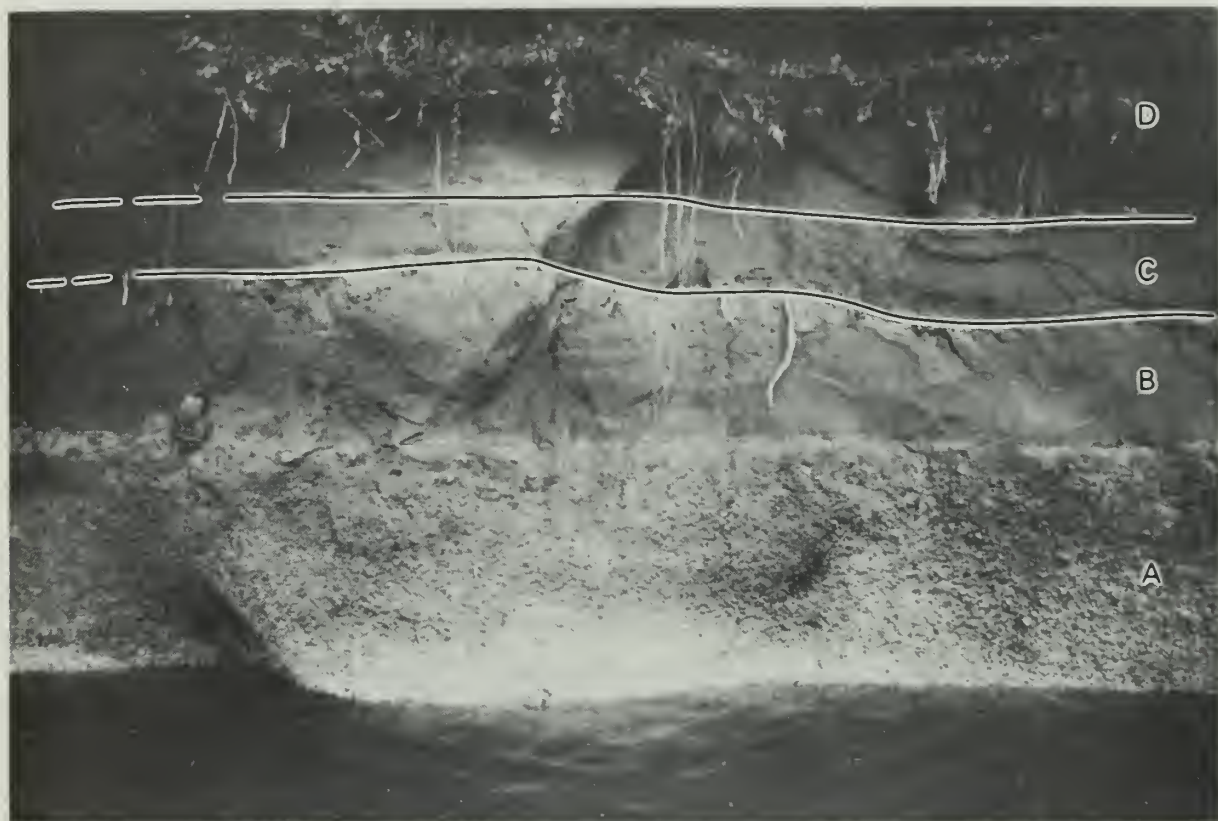


FIGURE 3.—Granular lahar (A) overlain by runout-flow deposits (B, C, D) along the eastern shore of Yale Lake. Contacts between runout-flow deposits are shown as solid lines, or dashed where contact is inferred. Exposure is about 4 m thick.

One lahar contains subangular to subrounded clasts as large as 20 cm. This deposit, exposed at lake level along the western shore of Yale Lake (location B, fig. 1) in the SE $\frac{1}{4}$ sec. 4, T. 6 N., R. 4 E., is about 2 m thick and overlies fractured Tertiary volcanic bedrock. Clast composition of this deposit differs from that of other lahar deposits in that about 10 percent of the clasts are composed of Tertiary rock.

Most of the sediment exposed along the shores of Yale Lake consists of alluvium with minor interbedded lahars. In places, the alluvium is 10 m or more thick, ranges in size from sand to boulders, and primarily consists of older Mount St. Helens lithologies. Biotite-bearing and pumice-rich lithologies were not observed, indicating that this fill postdates the Ape Canyon eruptive period. In the bluffs near the head

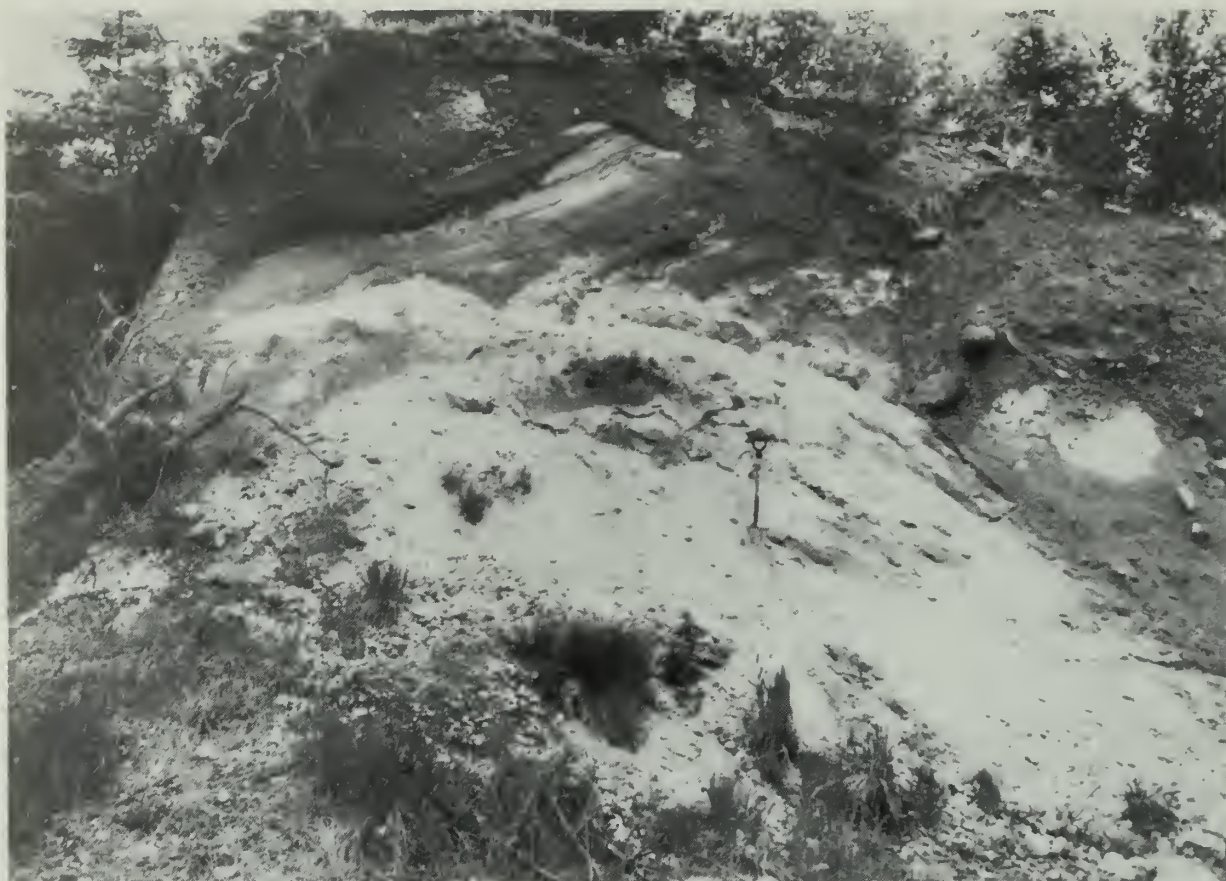
of the Speelyai Creek valley, along the western shore of Yale Lake, both modern and buried soil zones are exposed, each between 1 and 2 m thick, in a 10-m-thick alluvial fill. This fill is almost exclusively composed of older Mount St. Helens lithologies. Hyde (1975) correlated this fill with his older part of the Swift Creek assemblage.

The best exposed section of lahars in the Yale Lake area is in a gravel pit just west of the town of Cougar. Hyde (1975) considered these deposits to belong to the younger part of his Swift Creek assemblage. These lahars are relatively fine grained, consisting chiefly of sand, granules, and pebbles to small cobbles. The clasts in these deposits, generally smaller than 10 cm, are predominantly angular or subangular and are composed of older Mount St. Helens lithic debris.

YALE DAM TO LAKE MERWIN

Several lahar and lahar-related deposits are exposed about 35 km from Mount St. Helens between Yale Dam and Lake Merwin. One such deposit, unique in the Lewis River valley, is exposed in a gravel pit about 1.3 km west of Yale Dam (location C, fig. 1). This deposit is at least 10 m thick (the base is not exposed) and contains megaclasts incorporated in a very poorly sorted laharic matrix of subrounded to well-rounded, sand- to cobble-sized fragments. The megaclasts, as much as 3 to 5 m in maximum exposed diameter, consist of at least three distinct types: (1) One megaclast is composed of well-stratified fluvial deposits (fig. 4A) in which deformed sedimentary structures such as ripple marks are preserved. (2) Several megaclasts are massive and consist of pink, poorly sorted breccia composed of hydrothermally altered Mount St. Helens rocks from the ancestral volcanic complex (fig. 4B). These masses probably represent pieces of a debris avalanche that were eroded by the lahar. (3) A third type of megaclast occurs as pods of grayish, poorly sorted sand and granules with some small pebbles. This type represents masses of runout-flow deposits. Megaclasts derived from a pumiceous pyroclastic-flow deposit also have been observed by D.R. Crandell (written commun., 1986).

In addition to these unconsolidated megaclasts, the deposit also contains rounded clasts, generally less than 1 m in exposed diameter, of black andesites and basalts, weathered Tertiary volcanic rocks, and other non-Mount St. Helens lithologies derived from the Lewis River valley. The dominant clast type, however, is older Mount St. Helens dacites and andesites. Pre-Mount St. Helens lithologies make up about 15 percent of the clasts. In addition, the deposit contains a small percentage of prismatically jointed dacite clasts from Mount St. Helens that are generally less than 20 cm in diameter.



A



B

FIGURE 4.—Megaclasts of (A) stratified alluvium incorporated in lake-breakout-type lahar near Yale Dam (location C, fig. 1), and of (B) poorly sorted debris-avalanche deposit incorporated in lake-breakout-type lahar near Yale Dam. In each photograph shovel is 1 m long.

The significant rounding of the fragments in the deposit matrix and of many of the larger clasts, and the relatively large proportion of non-Mount St. Helens lithologies, indicate that alluvium was the primary source of material. A significant amount of incorporated alluvium in a lahar is characteristic of a flood-surge origin, as documented in the Toutle River valley by Scott (1985b). Newhall (1982) has proposed that the large lahar deposit resulted from the breaching of a lake impounded in the Lewis River valley by a debris avalanche during the Cougar eruptive period. The megaclasts of stratified alluvium and runout-flow deposits represent material plucked from the valley floor and incorporated into the flow, whereas the megaclasts of poorly sorted ancestral cone breccia are interpreted to be fragments of a debris avalanche. Given the lack of unequivocal debris-avalanche deposits upstream, however, it is not known if the megaclasts originally were eroded from a yet older debris avalanche, whether a debris avalanche formed a natural dam, or where the dam was located. The hypothesis of Newhall (1982) is a reasonable scenario, however. Although the prismatically jointed clasts in the deposit were clearly hot at some time, they may have been associated with a debris avalanche, or they may have been simply eroded from another deposit during emplacement of the lahar. Generally, lahar deposits known to be the distal equivalents of lithic pyroclastic flows contain a much larger percentage of prismatically jointed clasts than is observed in this deposit (Scott, 1985b).

Although a possible debris-avalanche deposit near Swift Dam is thought to be of Cougar age, the age of the lahar deposit exposed in the gravel pit is uncertain. D.R. Crandell (written commun., 1986) has assigned the lahar to the Cougar eruptive period. However, Hyde (1975) has ascribed the deposit to his younger part of the Swift Creek assemblage, which is now interpreted as originating during the Swift Creek eruptive period (table 1). Lack of a significant degree of soil development at the top of this lahar suggests to us that perhaps it may be even younger than Swift Creek age. The surface of the deposit, however, has been disturbed by logging and by the construction of Yale Dam, so that some of the apparent lack of soil development may be the result of soil removal. No deposits have been found upstream from Swift Dam to indicate that a lake was present for any significant length of time, leading Hyde (1975) to conclude that the Lewis River has been blocked only temporarily during the eruptive history of Mount St. Helens. This conclusion corresponds with the generally brief histories of lakes dammed by debris avalanches and other mass movements (Meyer and others, 1985; Costa and Schuster, 1987). Unfortunately, no suitable material has been found to precisely date the lahar deposit.

Lahars are well exposed in roadcuts about 1.5 km farther west, immediately north of the State Highway 503 bridge over the Lewis River

(location D, fig. 1). In a small borrow pit about 300 m north of the bridge, a lahar at least 2 m thick contains subrounded clasts of older Mount St. Helens rocks as large as 10 cm in a silty sand matrix (fig. 5). Several large pieces of fragmental charcoal were found in the top of this deposit that yielded a radiocarbon date of $13,415 \pm 310$ years. Overlying this deposit are two poorly sorted deposits of coarse sand to small pebbles. These deposits exhibit inversely graded bases and normally graded tops and represent a transition facies, characteristic of the interval of flow during which a lahar transforms to a runout flow. These deposits are 1.5–4.5 m thick and are capped by a locally developed soil approximately 0.5 m thick. A thin tephra unit separates the basal lahar from the overlying deposits. Hyde (1975) attributed the deposits to the younger part of the Swift Creek assemblage and speculated that the tephra deposit represents a layer of tephra set S. The radiocarbon age of the basal lahar indicates that it is indeed a product of the Swift Creek eruptive period (Mullineaux, 1986); an age of about 13,000 years corresponds with the degree of soil development.

In a roadcut about 100 m south of and downslope from this borrow pit, the Swift Creek age lahars are overlain, apparently unconformably, by two slope-mantling lahars (fig. 6). Each of these younger deposits is less than 1 m thick, massive, and composed of poorly sorted sand, granules, and small pebbles. On the slope above this roadcut, a veneer of the largest of these slope-mantling deposits is preserved. Small fragments of wood extracted from this veneer yielded a composite radiocarbon date of $3,920 \pm 365$ years. This radiocarbon date indicates that at least one, and probably both, of the flows that produced these slope-mantling deposits occurred during the Smith Creek eruptive period (table 1).

Near the roadcut, the Lewis River flows in a bedrock channel. If the reasonably certain assumption is made that the channel configuration of the Lewis River during post-Swift Creek time was similar to the present-day configuration, the depth of flow of the slope-mantling lahars can be estimated. The veneer deposit reaches an altitude of at least 105 m, which is about 45 m above the floor of the Lewis River channel beneath the bridge. Thus the post-Swift Creek age flows were at least 40 to 50 m deep at this site.

Paleohydrologic analyses of prehistoric lahars at Mount St. Helens suggest that lahars having depths in excess of 25 m may have mean velocities in excess of 20 m/s (Scott, 1986). For comparison, the 18 May 1980 North Fork Toutle River lahar had a peak-flow depth of about 16 m and a mean peak-flow velocity of about 9 m/s in the constricted channel reach near Kid Valley (Fairchild and Wigmosta, 1983). If we assume that the prehistoric lahars traveling down the Lewis River had a similar depth-velocity relation to that of these flows, then the mean velocities of the

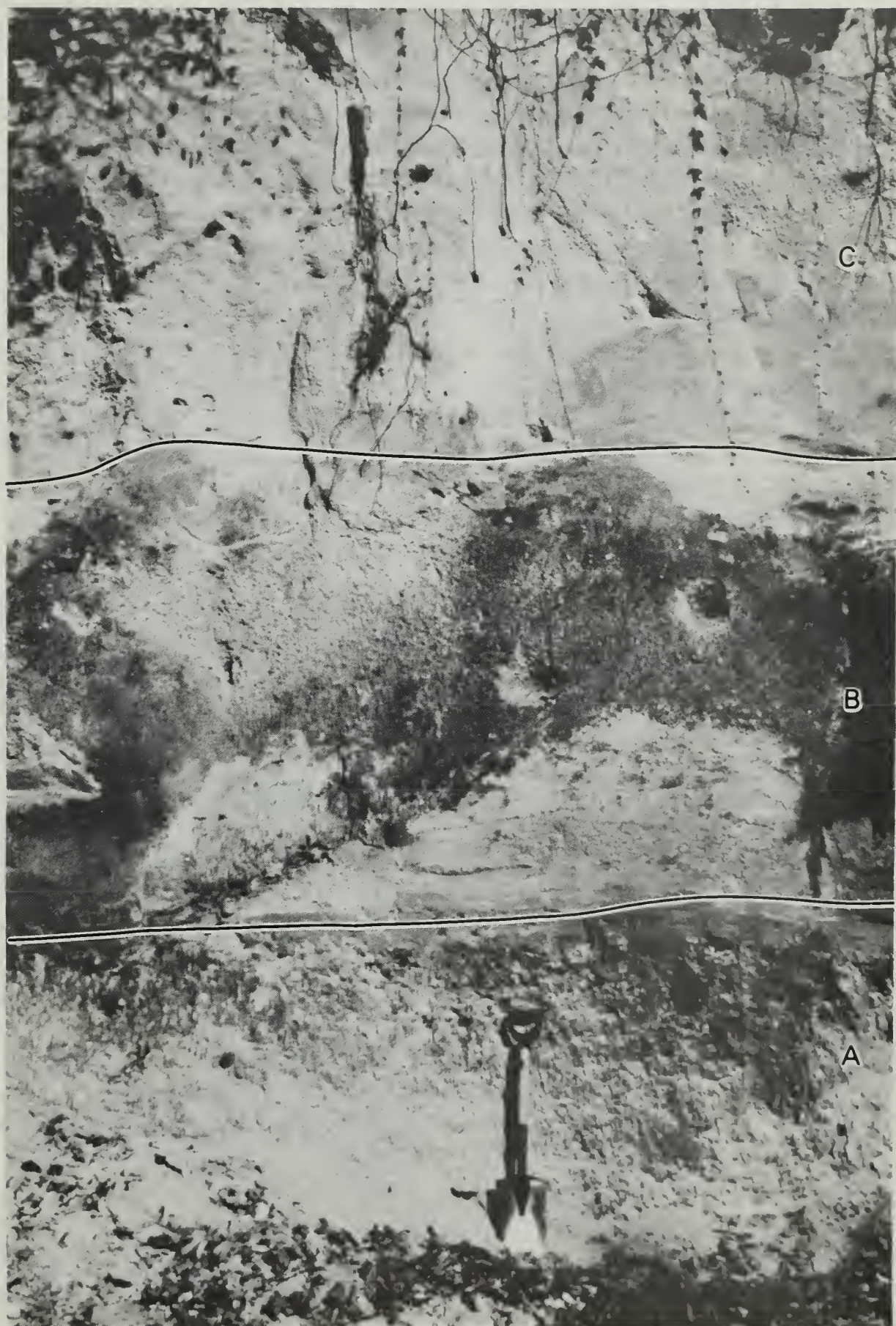


FIGURE 5.—Lahar (A) overlain by transition-facies deposits (B, C) in borrow pit north of State Highway 503 bridge over Lewis River (location D, fig. 1). Upper transition-facies deposit is overlain by a 0.5-m-thick soil. Lahar has a radiocarbon age of $13,415 \pm 310$ years. Contacts between deposits are shown as solid lines. Shovel is 1 m long.

post-Swift Creek age lahars, 40 to 50 m deep at the Lewis River bridge, are conservatively estimated to have been at least 10 to 15 m/s. This velocity and the topographic channel configuration at the bridge suggest that the post-Swift Creek age lahars had peak discharges of 130,000 to 200,000 m³/s at a distance of 35 km from the mountain. This estimated instantaneous discharge is about 10 times the mean annual discharge at the mouth of the Mississippi River (Oltman, 1968), but it is less than the peak discharge estimated for the largest prehistoric lahar in the Toutle River valley (Scott, 1986), which drains the north flank of Mount St. Helens.

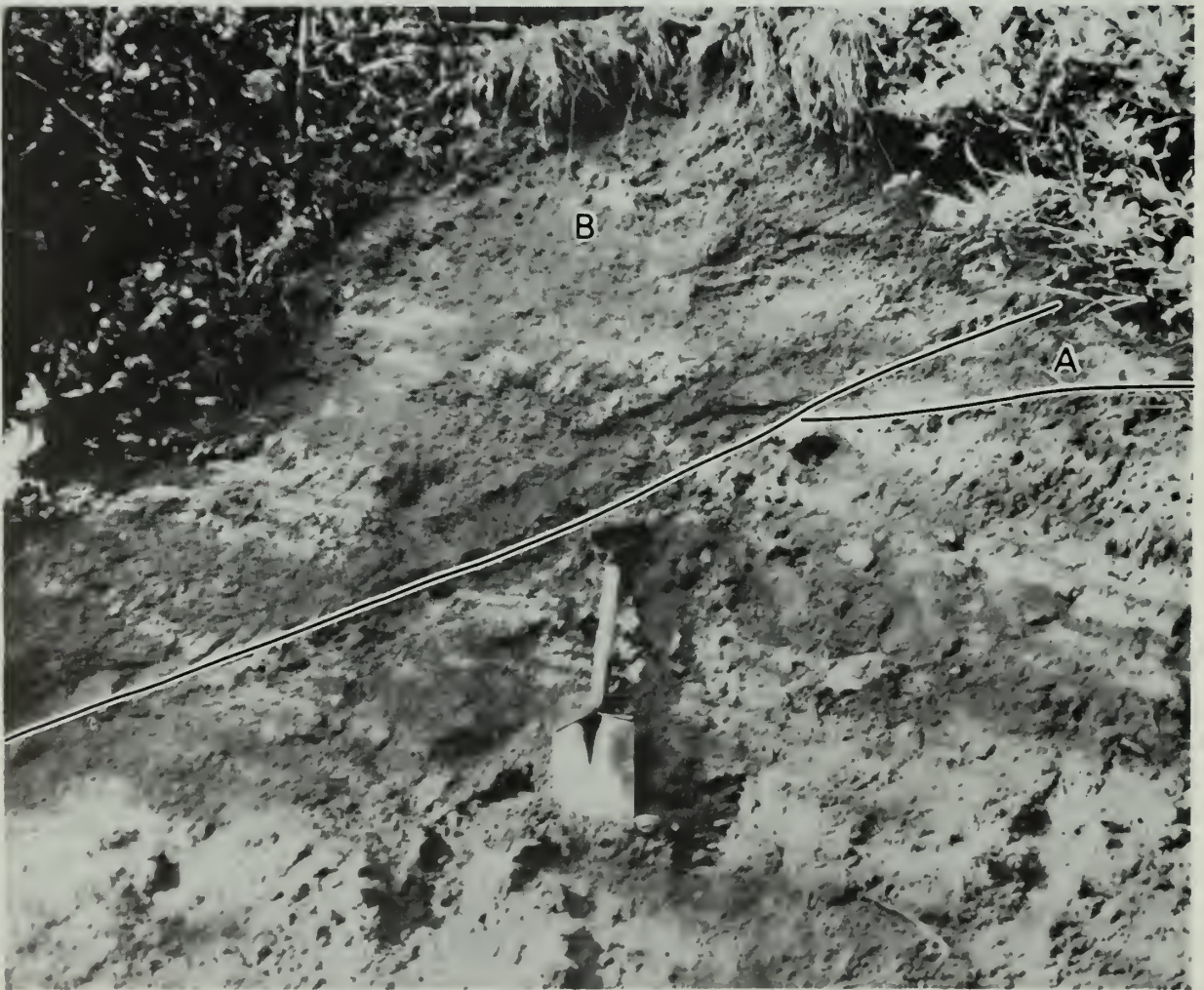


FIGURE 6.—Younger slope-mantling lahars (A, B) unconformably overlying older section of lahars in roadcut near State Highway 503 bridge over Lewis River (location D, fig. 1). Veneer deposit from these younger lahars coats valley wall above outcrop and has a radiocarbon age of $3,920 \pm 365$ years. Shovel is 1 m long. Solid lines delineate contacts.

SPEELYAI VALLEY AND LAKE MERWIN

Exposed in a gravel pit in the bay of Speelyai Creek near the upper end of Lake Merwin, 38 km from Mount St. Helens (location E, fig. 1), is a spectacular section of (1) a runout flow, (2) a lahar, and (3) fluvial deposits that locally contain thin lahars (fig. 7). The runout-flow deposit is at least 6 m thick and forms the basal unit in a fill that is about 20 m thick. This deposit, previously interpreted as a lahar by Hyde (1975), consists of poorly sorted coarse sand, granules, and some small pebbles that are mainly low-density, older Mount St. Helens rocks. It appears to be massive but exhibits some crude stratification; it is not dominated by the horizontal bedding that some investigators have indicated as being characteristic of hyperconcentrated streamflow deposits (for example, Smith, 1986). To date, this is the thickest runout-flow deposit known from Mount St. Helens. Overlying the basal deposit is a lahar about 10 m thick that contains angular clasts of older Mount St. Helens lithologies no larger than 10 cm. Capping these two deposits is a section of alluvium, interbedded with thin lahars, on which a well-developed soil has been formed. Near the top of the section, lenses of pumice mineralogically similar to tephra set J are found (table 1; Hyde, 1975). Hyde (1975) attributed this sedimentary section to his older part of the Swift Creek assemblage.

Deposits of a similar age almost certainly underlie much of the Speelyai Creek valley. Limited outcrops typically expose lahars containing relatively small clasts and runout-flow deposits generally less than 3 m thick, which interbed with alluvium composed of older Mount St. Helens lithologies. An outcrop at the intersection of State Highway 503 and Baker Road exposes a slightly indurated 0.8- to 1.5-m-thick lahar containing some angular pebbles of older Mount St. Helens lithologies. This lahar, which is capped by 1 to 1.5 m of well-developed soil, is underlain by alluvium from which fragmental pieces of charcoal were extracted. This charcoal yielded a date of $22,720 \pm 1,400$ radiocarbon years (table 2). The clast composition of these deposits indicates that the valley occupied by Speelyai Creek was formerly a channel of the Lewis River. Hyde (1975) suggested that the valley near Yale Dam in which the Lewis River presently flows was eroded when a pre-Fraser alpine glacier blocked the former main valley. Subsequent to the inception of Mount St. Helens, both valleys were aggraded. Deposits at the upstream end of the former main valley, which consist exclusively of alluvium and contain both a modern and buried soil, indicate that it was abandoned early in the history of Mount St. Helens. The presence of Cougar age tephra near the top of that fill (Hyde, 1975), the degree of soil development, and the lack of younger deposits indicate that this channel was completely abandoned during the later part of the Cougar eruptive period or shortly thereafter.

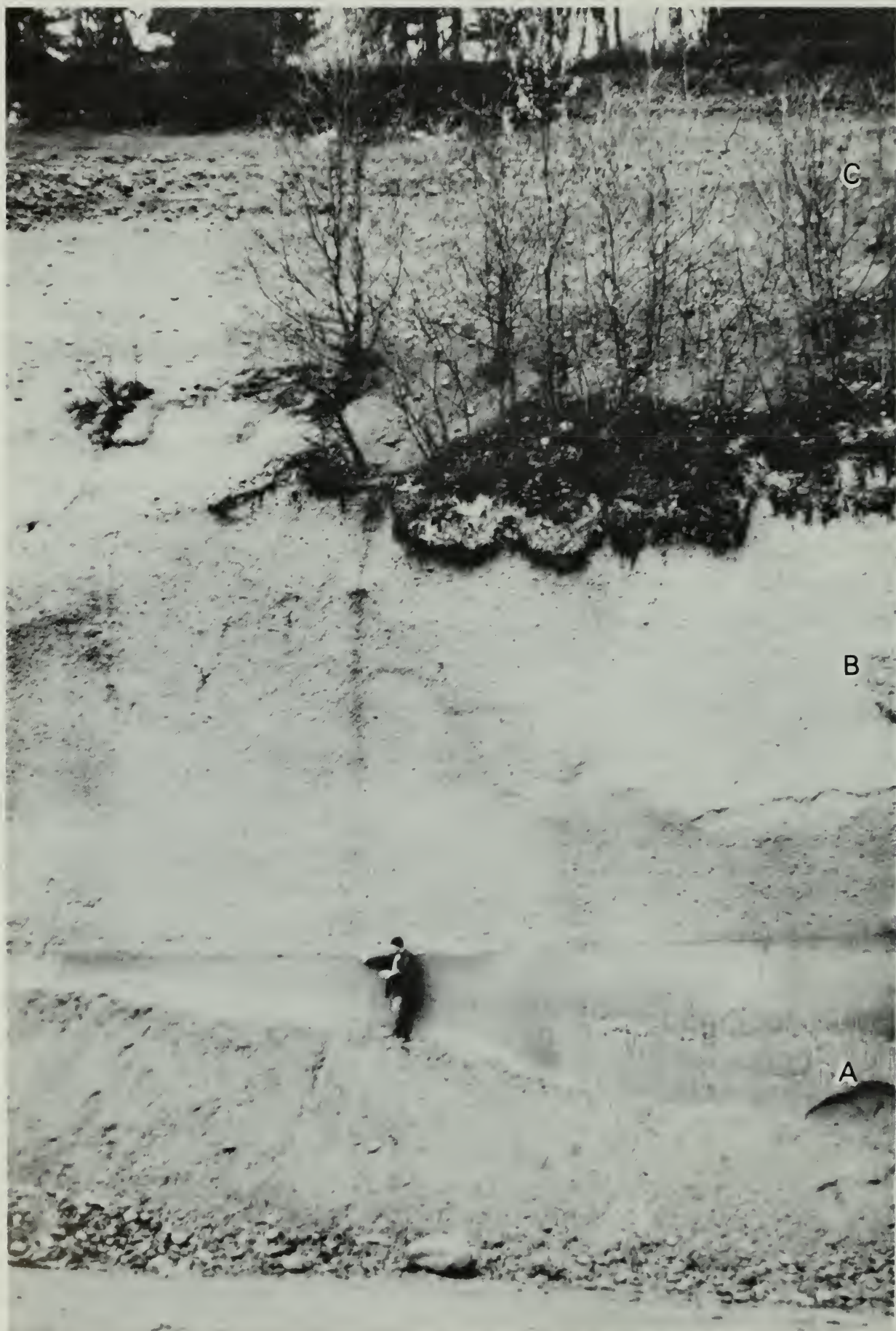


FIGURE 7.—Runout-flow (A), lahar (B), and alluvial deposits (C) in a gravel pit in the bay of Speelyai Creek (location E, fig. 1). Person is pointing to contact between runout flow and lahar. Thickness and development of soil horizon suggest that these deposits are of Swift Creek age (9,200–13,700 years) or Cougar age (18,200–20,400 years).

Stream piracy triggered by massive lahar-induced aggradation in the older channel probably caused the Lewis River to shift to its present course.

Along the shores of Lake Merwin, we have identified several lahar and runout-flow deposits. Runout-flow deposits are typically less than 1 m thick and are generally interbedded with lahars and alluvium. These deposits, the best examples of which are exposed several hundred meters downvalley from the mouth of Jim Creek, are typically unstratified. Some are ungraded; others are normally graded. A few of these deposits contain rare biotite-bearing pumice clasts of Ape Canyon age (table 1) as large as 6 cm. Lack of biotite content in the sand matrix of these deposits, in conjunction with their interbedded nature with sedimentary sections typically capped by well-developed soil horizons, suggests that they are of Cougar or Swift Creek age.

Some of the lahars around Lake Merwin contain a significant proportion of clasts that are pebble sized and larger and exhibit some degree of rounding. Such sedimentologic characteristics, similar in part to those of deposits of Pine Creek age in the Toutle River system, indicate lahars that have been bulked to a significant degree with eroded alluvium (Scott, 1985b). The best example of this type of deposit in the Lewis River valley is exposed at the mouth of Jim Creek, about 43 km from the mountain (location F, fig. 1). Here, a deposit about 3 m thick contains poorly sorted cobbles dispersed in a compact silty sand matrix (fig. 8). The basal 0.5–1 m of this deposit exhibit inverse grading; the upper 0.5–1 m exhibit normal grading of the coarse clasts. This deposit is overlain by weathered alluvium on which a soil was developed and subsequently buried. Thus, this deposit is of Cougar or Swift Creek age also.

Another lahar deposit along Lake Merwin that appears to be of similar age to that exposed near Jim Creek is composed of older Mount St. Helens clasts that are subangular to angular and as large as 2 m in diameter (location G, fig. 1). This deposit, 2 to 3 m of which are exposed, represents a lahar that did not bulk with a significant quantity of alluvium. Rather, it probably formed on the volcano and traveled at least 40 km while incorporating less streambed alluvium than many other lahars.

Alluvial deposits exposed about 50 m above the pre-lake valley floor along the north shore of Lake Merwin (location H, fig. 1) indicate that an extensive fill of Ape Canyon age extended throughout the lower Lewis River valley. Here, a 10- to 12-m-thick section of pumice-rich alluvial sand is exposed. Locally, sand beds contain rounded pumice clasts as large as 6 cm. Most of the pumice clasts contain biotite, and detrital biotite also is abundant in the sand beds. This lithologic composition is characteristic of Ape Canyon age products. The pumice content lends a distinct white color to the fill, which is remarkably similar to the fill of



FIGURE 8.—Cobble-rich flood-surge-type lahar of Cougar or Swift Creek age exposed near the mouth of Jim Creek (location F, fig. 1). Note inverse grading near the base and normal grading of coarse clasts near the top of the deposit. Shovel is 1 m long.

similar age, thickness, and extent in the Toutle-Cowlitz River system on the north side of the volcano (Scott, 1985b, 1986). Previously, deposits of Ape Canyon age in the Lewis River valley were known only as far downstream as Swift Dam.

DOWNSTREAM FROM MERWIN DAM

Immediately downstream from Merwin Dam, lahar and runout-flow deposits coat the upper valley wall in a narrow bedrock gorge to an elevation of about 30 m above the valley floor (location I, fig. 1). The sequence here includes, from oldest to youngest, two massive, sand and granule runout-flow deposits, each of which is about 1 m thick and capped by a clayey soil horizon; and two overlying lahars, the lower of which is less than 0.5 m thick, is weathered, and contains pumice mineralogically similar to tephra set S. The uppermost slope-mantling lahar is as much as 1 m thick, inversely graded, and contains clasts only as large as 5 cm (fig. 9). Smaller pebbles and granules generally are subangular to angular,

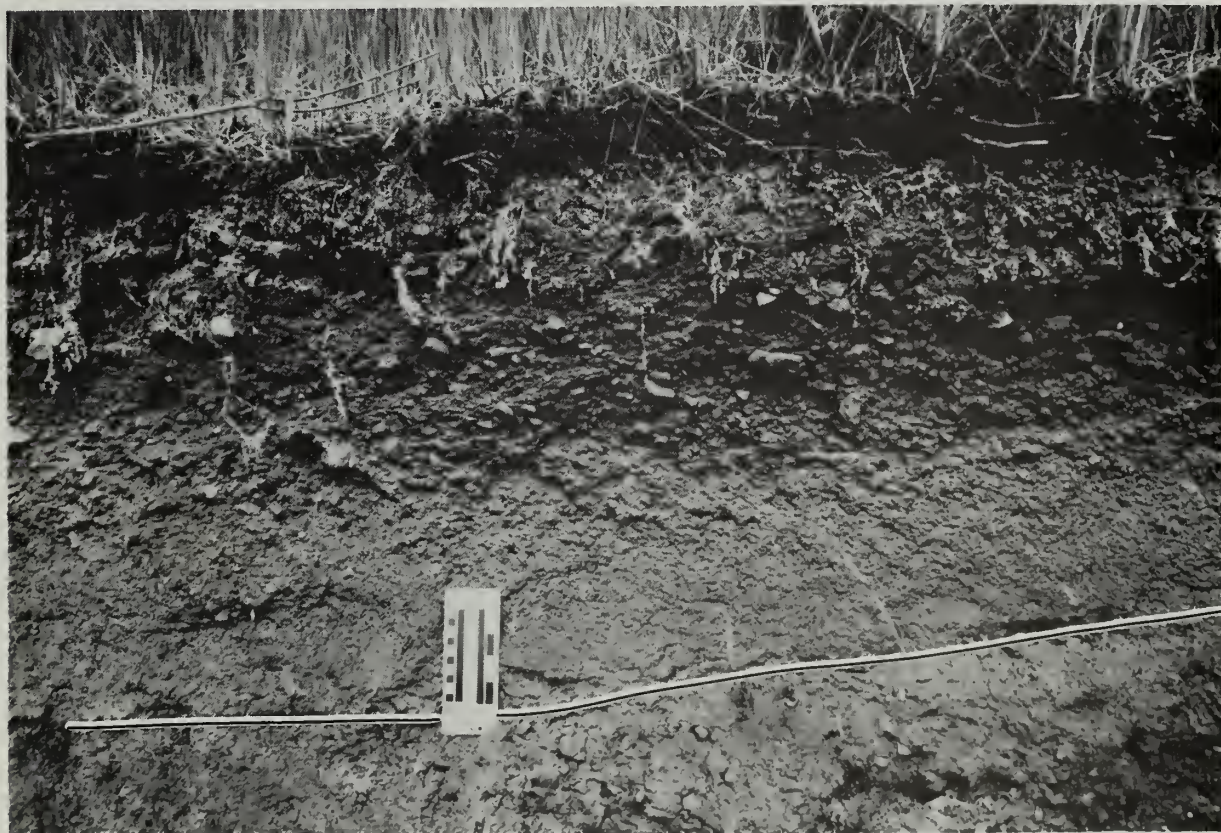


FIGURE 9.—Slope-mantling lahar deposit from the Smith Creek or Pine Creek eruptive period exposed below Merwin Dam (location I, fig. 1). Solid line delineates basal contact. Scale is 10 cm long.

whereas the larger pebbles typically are subangular to subrounded. Lack of weathering indicates that this uppermost deposit is significantly younger than the underlying units, though its clasts are mineralogically similar to the older Mount St. Helens lithologies. The texture and slope-mantling nature of this deposit suggest that it could correlate with one of the slope-mantling lahars exposed near the State Highway 503 bridge between Lake Merwin and Yale Dam.

The farthest known downstream extent of Mount St. Helens lahars is about 1 km west of Merwin Dam, along a clearing for power-transmission lines (location J, fig. 1). Here, two exposures show that a gently sloping surface 40 m above the valley floor is covered by a veneer of fine-grained debris interpreted to represent a facies transitional from a lahar to a runout flow. The deposit, about 1.5 m thick, is poorly sorted and inversely graded from coarse sand near the base to fragments as large as 5 cm at the top (fig. 10). Fragments typically are subangular to angular, but a few show a significant degree of rounding. This deposit overlies a lahar that contains small clasts and exhibits soil development. The uppermost deposit probably correlates with the slope-mantling lahar observed at Merwin Dam and may be finer grained at this location because of valley widening.

The presence of the slope-mantling deposit downstream from Merwin Dam clearly shows that the lahar traveled at least 50 km downvalley from the volcano. Furthermore, the existence of the deposit on the gently sloping terrain above the narrow bedrock channel through which the river flows indicates that at peak flow the lahar must have been at least 40 m deep if it is assumed that the shape of the valley has not changed significantly since the lahar occurred.

The mean peak-flow velocity of this lahar may have been 10 to 15 m/s at this point. If so, the present channel configuration suggests that this lahar had a peak discharge of 90,000 to 140,000 m³/s at this point.

FLOOD-PLAIN AGE AND DEVELOPMENT IN THE LOWER LEWIS RIVER VALLEY

Throughout its history, the area of the lower Lewis River valley near where the town of Woodland (fig. 1) now sits has been dominated by fluvial deposition. Exposed deposits in this reach of the valley consist mainly of interbedded, stratified clayey silts; silty sands; and massive to cross-stratified beds of sand. Exposed units typically vary from less than 1 to about 3 m in thickness.

Sedimentation in the lower Lewis River valley has been influenced by several geological processes. During a Pleistocene glaciation prior to the inception of Mount St. Helens, ice extended to within 8 km of the present

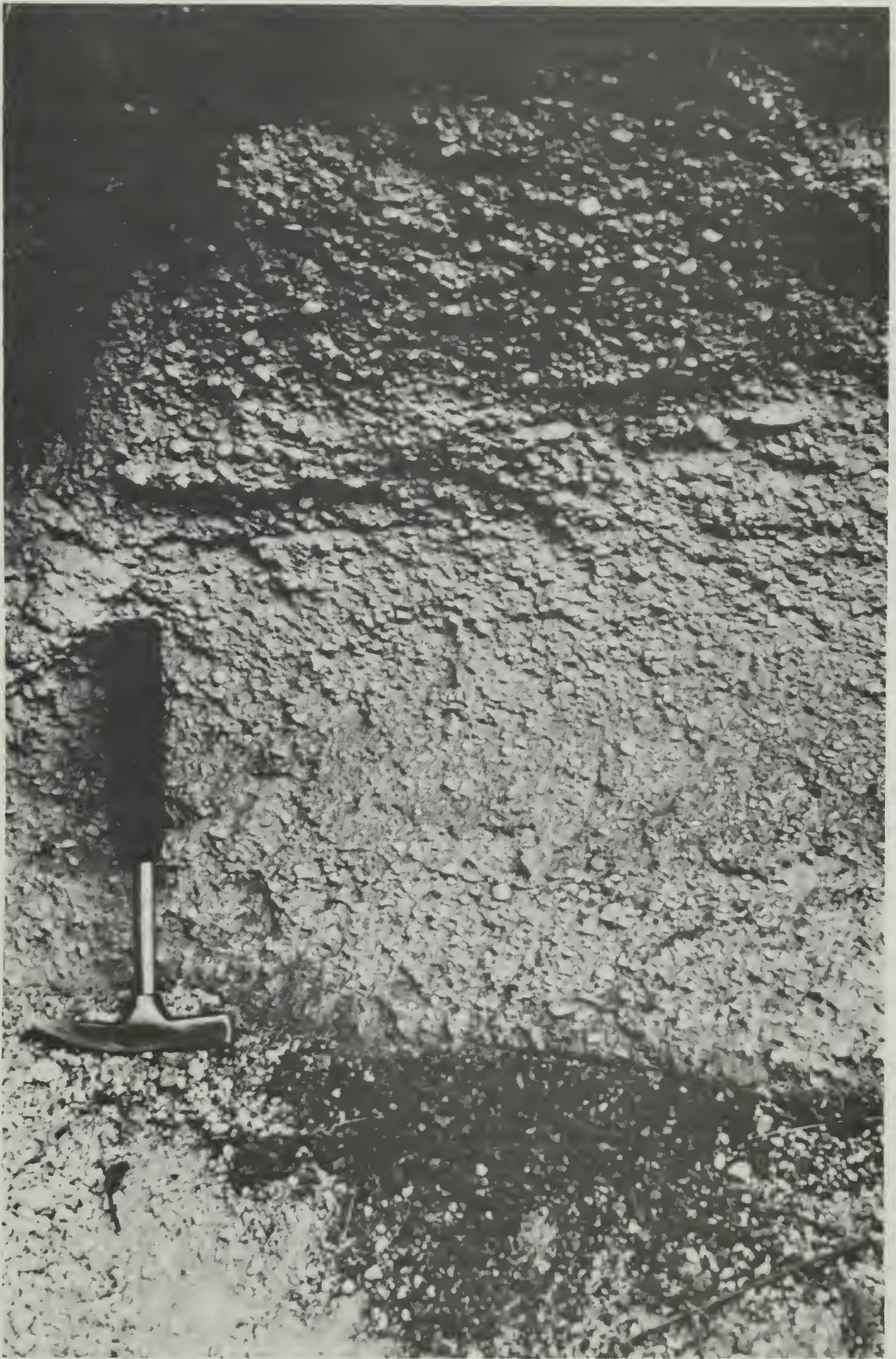


FIGURE 10.—Transition-facies deposit exposed about 1 km downstream from Merwin Dam (location J, fig. 1). Note inversely graded texture and lack of weathering. Hammer is 30 cm long.

site of Woodland (Mundorff, 1984), deposited glacial drift, and induced glaciofluvial sedimentation. Since the inception of Mount St. Helens about 50,000 years ago, the valley has been affected by glaciofluvial sedimentation from, and alteration of baselevel by, the Fraser glaciation (which achieved a maximum stand about 20,000 years ago; Crandell and Mullineaux, 1973; Hyde, 1975), by many of the colossal Lake Missoula floods on the Columbia River between 19,000 and 13,000 years ago (Waite, 1980), and by episodic alluviation by volcanoclastic sediment produced during eruptions of the volcano. During at least postglacial time, alluviation in the lower valley has been dominantly influenced by the episodic influx of volcanoclastic sediment upstream. Such radical influx of sediment, and the consequent excessive stream sediment load, has caused episodic aggradation in the lower Lewis River valley similar to that occurring today in the lower Toutle and Cowlitz Rivers (fig. 1; U.S. Army Corps of Engineers, 1984). Drilling logs (Washington State Department of Ecology, written commun., 1986) report pumice-bearing sands to an average depth of about 15 m near the town of Woodland, and a few report pumice-bearing units to depths of as much as 35 m, indicating that sediment related to the volcano composes a large part of the fill in the lower valley.

The maximum strandline of the colossal floods on the Columbia River near Woodland (about 120 m in elevation) indicates that the Lewis River valley was affected by backwater flooding rather than through-flooding. In the Columbia River drainage basin, many of the tributary channels affected by backwater flooding were sites of deposition rather than erosion (Bretz, 1929; Waite, 1980, 1984, 1985), even when the peak-flow depth was on the order of several hundred meters. We infer that the lower Lewis River valley was probably a site of deposition, or at worst a site of mild erosion, during passage of the great floods, although deposits from those floods have not been recognized. Therefore, the thick, volcanically related alluvial fill in the lower Lewis River valley probably represents a nearly complete stratigraphic record since the inception of the volcano.

Although the petrologic character of the deeply buried pumice in the alluvial section near Woodland is unknown, it may be from the Ape Canyon eruptive period. The presence of an extensive Ape Canyon age fill is consistent with observations made by Scott (1985b, 1986) in the Toutle River valley and also is consistent with the thick fill of Ape Canyon age observed farther upstream.

Remnants of several stages of alluviation are present in the lower Lewis River valley. The oldest exposed fill, of Pleistocene age, is represented by a flat surface at an altitude of about 60 m (Mundorff, 1964). A remnant from a younger fill was found on the south side of the valley, 8 to 12 m above the present flood plain (SE $\frac{1}{4}$ sec. 18, T. 5 N., R. 1 E.).

This younger terrace is underlain primarily by fine- to medium-grained alluvial sands that are cross-stratified and laminated in their upper few meters and generally massive in the lower portions of the exposure. These deposits contain biotite, similar to that found in products of the Ape Canyon eruptive period. Small fragments of charcoal retrieved from the exposure of this terrace yield a composite radiocarbon age of 695 ± 340 years. This terrace represents alluviation by material reworked from deposits farther upstream because products of only the Ape Canyon eruptive period contain biotite, and deposits of that age are not exposed in the lower valley.

The youngest and most prominent geomorphic feature in the lower Lewis River valley, which we informally refer to as the Woodland terrace, forms a broad flat surface at an elevation of about 6 to 8 m above the present Lewis River flood plain. The lower 3 m or so of deposits beneath this terrace are composed of stratified clayey silt and massive, mottled silty fine sand. These fine-grained sediments are overlain by well-sorted, cross-stratified to nearly massive medium-grained sand. The upper, more massive grayish sand deposit forms lenticular bedding and contains rounded pebble-sized fragments of white pumice. Crandell and Mullineaux (1973) observed gray pumice-bearing sands within a 7.5-m-high terrace along the reach of river extending 8 km upstream from Woodland. They stated that the pumice was mineralogically similar to that of tephra set P and inferred that those fluvial sediments were the downstream correlative of the post-Y part of the assemblage of deposits exposed in Pine Creek.

During our investigation of this terrace, fragments of wood were collected from a zone near the contact between the stratified clayey silt and massive silty fine sand (SE $\frac{1}{4}$ sec. 18, T. 5 N., R. 1 E.). This wood, extracted from a level at least 1 m below the pumice-bearing sands, had a radiocarbon date of 440 ± 70 years. The white pumice in the fill above this contact belongs to tephra set W rather than set P. Although both tephra sets have a similar mineralogic composition (Mullineaux and others, 1975; Mullineaux, 1986), the minimum refractive index of hypersthene in set W pumice is greater than 1.70, whereas that of hypersthene in set P pumice is less than 1.70 (Mullineaux and others, 1975). Of 10 pieces of pumice examined from this fill, 7 contained hypersthene having a minimum refractive index of greater than 1.70. The radiocarbon date and pumice identification indicate that the upper part of this sedimentary fill was formed in response to aggradation during the Kalama eruptive period (table 1).

To date, flows of volcaniclastic debris bearing set W pumice are not known to have entered the Lewis River drainage basin. The set W pumice was deposited in the Lewis River drainage basin only as tephra fall east of Mount St. Helens during the early part of the Kalama eruptive period.

This indicates that the W pumice in the fill at Woodland either was eroded from hillslopes east of the volcano or that the alluviation in the lower Lewis River valley during the Kalama eruptive period was related to heavy tephra fall directly into rivers in the Lewis River drainage basin. A recent study of erosion of 1980 Mount St. Helens tephra by Collins and Dunne (1986) indicates that the rate of erosion of tephra on hillslopes rapidly declined within a few years after the eruption without significant repopulation of vegetation. This result suggests that if the alluviation during the Kalama eruptive period in the lower Lewis River valley did not occur immediately after tephra fall in the drainage basin, then it probably occurred within a few years after the tephra fall.

Lahars apparently did not reach the lower Lewis River valley; flood plains were aggraded primarily by lahar-induced fluvial sedimentation. Depositional evidence suggests that most of the lahars that flowed down the Lewis River valley lost much of their coarse debris and had undergone or were undergoing a transition to runout flow by the time they reached the present site of Merwin Dam. These transformations were caused primarily by the granularity of the flows (less than 2 percent clay). Scott (1985b) observed that lahars having clay contents of more than 3 percent would travel great distances from their source (as much as 100 km or more) without losing textural integrity, but that relatively noncohesive (less than 3 percent clay) lahars invariably underwent transformation to runout flows. The granularity of the latter lahars increased their ability to mix with overrun streamflow, which resulted in their consequent transformation. Moreover, although the Lewis River flows through a bedrock gorge near Merwin Dam, the river valley emerges into a broad flood plain a few kilometers downstream from the dam. This valley widening additionally enhanced the flow transformation of lahars. By the time the initially sediment-rich lahars reached the lower part of the valley, they had become completely transformed, and alluviation dominated the depositional process.

LAHAR AND DEBRIS-AVALANCHE HAZARDS IN THE LEWIS RIVER VALLEY

PRESENT ERUPTIVE PERIOD

Changes in the configuration of Mount St. Helens as a consequence of the paroxysmal 1980 eruption, combined with the construction of three hydroelectric dams (fig. 1) during the past 50 years, have diminished the direct threat of lahars that may reach the lower Lewis River valley. Swift Reservoir, however, lies immediately downvalley from Mount St. Helens and could be threatened if large lahars were to occur on the south or southeast flank of the volcano. Removal of a vast portion of the volcano

by the 1980 debris avalanche has greatly reduced the risk of another debris avalanche during the present eruptive period.

Rain-induced lahars generated on the south and southeast flanks of the volcano probably would be small and would not flow to any significant distance beyond the base of the cone. Major (1984) documented posteruption, rain-induced lahars that flowed no more than 6 km from the crater rim on the southwest flank of the volcano, and both R.P. Hoblitt (U.S. Geological Survey, oral commun., 1987) and T.C. Pierson (U.S. Geological Survey, oral commun., 1987) have documented rain-induced and glacial-meltwater-induced lahars that traveled no farther than the Pine Creek-Muddy River debris fan at the base of the east flank of the cone. Rain-induced lahars pose no serious threat to Swift Reservoir.

Given the present configuration of the volcano and the present style of eruption (periodic extrusion of lava lobes onto the dome, endogenous dome growth, and small explosions), lahars generated by eruptions will affect primarily the Toutle River system, possibly for the next several decades or centuries. Lahars could threaten Swift Reservoir if the style of eruption changes, however. Such lahars may occur if large-scale explosive activity resumes and causes pyroclastic flows that melt snow and ice outside of the crater on the volcano's upper flanks, or if the location of the vent changes and causes a dome to form on the volcano's south-southeast flank, similar to several domes formed during past eruptions (Verhoogen, 1937; Hoblitt and others, 1980). Eruption of a lava flow from a vent on the south-southeast flank of the volcano could also melt snow and ice and produce a lahar. An obvious concern then is what size lahar might reach Swift Reservoir should these events occur.

Emplacement of a flank dome or eruption of a lava flow probably would affect a limited area of the volcano. However, a pyroclastic flow generated by collapse of an eruption column could affect a broad area of the volcano, and thus this is thought to represent a worst-case scenario.

Crandell and Mullineaux (1978) suggested that the largest single lahar that might be expected to enter Swift Reservoir possibly would have a volume of no more than 125 million m^3 . They arrived at this value by assuming, as a worst case, that a pyroclastic flow, similar in size to one that occurred during the Pine Creek eruptive period, would melt as much as 5 m of snow (density = 0.25) over an area of 30 km^2 to produce 35 to 40 million m^3 of water. They further assumed that an average lahar has a volumetric distribution of roughly 65 percent sediment and 35 percent water, and that this volume of water potentially could mobilize about 75 million m^3 of volcaniclastic debris to produce a lahar with a volume of about 110 million m^3 . They then rounded their estimate conservatively upward. In the spring of 1980, prior to the 18 May eruption, Swift Reservoir was drawn down to accommodate a potential fill of that size (Miller

and others, 1981). This amount of drawdown proved adequate only because the catastrophic explosive phase of the 1980 eruption was fortuitously directed northward. If the 1980 debris avalanche occurred on the volcano's south or southeast flanks, the reservoir possibly would have been overwhelmed and much water displaced.

Recent snow studies at Mount St. Helens (R. Denlinger, U.S. Geological Survey, oral commun., 1987) indicate that Crandell and Mullineaux (1978) underestimated typical snow density. In the Mount St. Helens crater, fresh snow has an average density of about 0.3, but typical snow has a density that ranges from 0.4 to 0.6. By late spring, snow density is as much as 0.75. If we assume that 4 m of snow having an average density of 0.5 is incorporated by the postulated pyroclastic flow of Crandell and Mullineaux (1978), and that melting is 100 percent efficient (that is, all melted snow is converted to water with no loss by steam), such an event could generate as much as 60 million m³ of water. That volume could possibly produce a lahar with a volume of about 170 million m³. The lahar, however, could continue to incorporate sediment, so a larger volume may be possible.

A recent report by Cassidy and others (1980) suggests that the maximum probable lahar that could reach Swift Reservoir probably is smaller than the estimate of Crandell and Mullineaux (1978) and may not exceed 62 million m³. Although Cassidy and others (1980) assume the same input hydrograph (35 million m³ of water) as Crandell and Mullineaux (1978), they assume that the flowing sediment-water mixture is composed of 57 percent water by volume instead of about 35 percent. That assumption means that the flowing mixture that reaches Swift Reservoir is not a lahar (defined here as a debris flow generally containing 60 percent sediment by volume or 80 percent by weight) but rather is a moderately dilute hyperconcentrated streamflow (Beverage and Culbertson, 1964). Along the channels of Pine Creek, Swift Creek, and Muddy River, abundant sediment is available for entrainment by an evolving lahar. Although factors that control the bulking of lahars by sediment entrainment are not yet adequately quantified, the geological record of lahar behavior in both the Lewis and Toutle River systems indicates that the conservative approach of Crandell and Mullineaux (1978) is more technically valid for estimating lahar volume.

FUTURE ERUPTIVE PERIODS

DEBRIS AVALANCHES

Possibly the most catastrophic event from a future eruption of Mount St. Helens that could affect the Lewis River valley downstream from the volcano is the direct impact of a large debris avalanche (>1 km³) on

Swift Reservoir. In hazard assessment, an obvious concern is the travel distance of such a debris avalanche.

A simple method for estimating the runout distance of a large debris avalanche is based upon the ratio of vertical drop (H) to travel distance (L) (Schuster and Crandell, 1984). If we assume that a debris avalanche will have a volume of at least 1 km^3 , and that it will have an H/L ratio similar to that of large volcanic debris avalanches worldwide (Voight and others, 1983; Siebert, 1984), the travel distance can be estimated by

$$L = H/f,$$

where f is the equivalent coefficient of friction. The vertical drop from the present rim of the volcano to the Swift Creek valley, 8 km south of the former summit of the volcano, is about 1,700 m. The estimated travel distance of a debris avalanche having that vertical drop and a coefficient of friction conservatively estimated to be 0.065 (Voight and others, 1985, fig. 5) is about 26 km, a distance similar to the travel length of the 1980 debris avalanche. If we assume a value of 0.09 for f (the estimated equivalent coefficient of friction of the 1980 debris avalanche (Voight and others, 1983)), the estimated travel distance is about 19 km. The distance between Swift Dam and the former summit of Mount St. Helens is 15 km, a distance well within the estimated travel length of a future, large debris avalanche. Furthermore, the gradient between Mount St. Helens and Swift Reservoir along Swift Creek is greater than that of the North Fork Toutle River and thus enhances avalanche mobility down Swift Creek.

The renewed risk of a debris avalanche could justify drawing Swift Reservoir down to the level of dead storage, depending on the focus of activity as indicated by precursor seismicity and geodetic measurements. A debris avalanche from the south or southeast flanks of the volcano similar to the 1980 event would have a devastating impact on Swift Reservoir. If a debris avalanche into any part of the Swift Creek, Pine Creek, or Muddy River drainage basins had a volume only one-half that of the 1980 avalanche (estimated to be 2.8 km^3 by Voight and others, 1981), and if only one-fourth of that volume reached the reservoir, more than 300 million m^3 of debris would impact the reservoir. Deposition of such a vast quantity of volcaniclastic sediment, equivalent to one-third the maximum storage capacity of Swift Reservoir, could have devastating consequences.

If such a debris avalanche occurred in the Pine Creek-Muddy River system and passively entered a capacity-full Swift Reservoir at its eastern end, it would raise the level of the reservoir 17 m, which would cause overtopping of the dam. However, such a debris avalanche would not enter the reservoir passively; rather, it would enter the reservoir with

a probable high velocity (the average velocity of the 1980 debris avalanche was 35 m/s (Voight and others, 1983)), which would generate a large translational wave on the lake.

Dimensions of such a debris avalanche can be approximated by using the previously estimated travel length (26 km) and by routing the avalanche down the shortest travel path to the east end of the reservoir (18 km down Pine Creek). The estimated travel length of the postulated debris avalanche suggests that it would travel about 8 km into the reservoir. Dividing the hypothetical volume of such a debris avalanche by this travel length, and then matching avalanche width and thickness with the cross-sectional area of the Lewis River valley at the east end of the reservoir, indicates that a debris avalanche with a volume of 300 million m³ could be about 30 m thick and 1,200 m wide when it enters the reservoir. The mean depth of Swift Reservoir at capacity is presently about 50 m. Thus, a debris avalanche 30 m thick would approximate a wall moving into the reservoir.

The size of a wave generated on Swift Reservoir by the impact of such a large, fast-moving debris avalanche may be estimated by using a two-dimensional approximation for a horizontally moving wall (Noda, 1970). The maximum wave amplitude (η) at a distance $x/d = 2$ is given by

$$\frac{\eta}{d} = 1.32(V/\sqrt{gd}),$$

where d is the mean water depth of the reservoir, V is the velocity of the avalanche upon impact with the reservoir, g is the acceleration due to gravity, and x is the distance of maximum wave amplitude from the point of impact. This theory predicts that the maximum wave amplitude (above mean water level) is about 104 m at a distance of about 100 m in front of the debris avalanche.

Although such a wave is enormous, it is not improbable nor is it unprecedented. A landslide into Lituya Bay, Alaska, in 1958 generated a large gravity wave that left trimlines on a rock spur as much as 520 m above the water surface (Miller, 1960), and back calculations suggest a maximum wave height of about 100 to 300 m (Slingerland and Voight, 1979). Where Lituya Bay empties into the Gulf of Alaska, wave height was estimated to be about 25 m above trees growing on a bay-mouth spit (Slingerland and Voight, 1979). It is of interest to note that the geometry and dimensions of Lituya Bay are similar to Swift Reservoir, and that the landslide that caused the giant wave in Lituya Bay had a volume 10 times smaller than the volume of debris avalanche entering Swift Reservoir postulated here. A wave of such magnitude would certainly overtop Swift Dam at water levels near capacity and might possibly precipitate dam failure.

If such a debris avalanche traveled down Swift Creek, the most direct route and the approximate path of a prehistoric debris avalanche, it might destroy Swift Dam and displace or release much water. Even if the dam was not destroyed, such a debris avalanche could overwhelm the valley and add to the height of the dam, with the threat of later failure and consequent lake-breakout lahars.

Failure of Swift Dam, and the concomitant release of water, could possibly cause successive dam failures downstream. The effects of sequential dam failure in the lower Lewis River valley would be devastating. The final safety assessment report for the Trojan nuclear plant (Portland General Electric Company, 1976) models sequential dam failure on the Lewis River and shows that the flood wave would reach Woodland within 1 hour and would inundate the lower Lewis River valley to an altitude of about 12 m above sea level, inundating the town. Such a flood would not affect the nuclear plant, 28 km downstream from Woodland (Portland General Electric Company, 1976).

LAHARS

In addition to a possible debris avalanche, lahars may also affect Swift Reservoir in future eruptive periods. Although lahars large enough in volume to reach Swift Reservoir can be generated in many ways, the following discussion of the hazards posed by lahars is limited to perhaps the three worst scenarios, each of which is capable of producing lahars of very large volume.

(1) Dewatering of a debris avalanche. Although the magnitude of the paroxysmal 1980 eruption was small in comparison with many past eruptions of the volcano, the 1980 debris-avalanche deposit is the largest volcanoclastic deposit in the history of the volcano. Dewatering of parts of that deposit produced the largest lahar in 1980 (Janda and others, 1981), which had an estimated volume of 140 million m³ (Fairchild and Wigmosta, 1983). Because of the modest size of the volcano's cone, a future debris avalanche from the south or southeast flanks of the volcano probably will not exceed the size of the 1980 avalanche, and it may likely be smaller. If such a debris avalanche occurs and does not directly impact Swift Reservoir, lahars formed by dewatering of the deposit are likely.

Steeper channel gradients on the volcano's southern sector and perhaps a wetter debris avalanche could combine to promote greater erosion of the deposit during dewatering, potentially generating a lahar with a volume greater than the largest 1980 lahar. Because of the unknown size, water content, and rate of erosion of a future debris-avalanche

deposit, the 1980 lahar formed by avalanche dewatering may approximate the possible maximum size of this type of lahar for planning purposes.

(2) Breaching of a natural dam and consequent lake breakout. Estimation of sizes of lahars that could be produced by flood surges from breaching of a volcanoclastic dam is more difficult. Although the distribution of deposits in the Lewis River valley shows that repeated dams must have existed in the past, and indeed many deposits exhibit characteristics of flood-surge origin, the preservation and exposure of individual lahars are at best spotty, and thus volume estimates cannot be made. However, the filling of a natural reservoir and breaching of a dam may require a period of months or years, which would allow time for mitigation and reduce the relative hazard of this type of flow.

If a debris avalanche flowed down Swift Creek or Pine Creek, it is unlikely that a lake would form upstream from Swift Reservoir because there are no significant channels tributary to these main channels. However, if a debris avalanche flowed down Muddy River, the channels of Smith Creek and Clearwater Creek could be blocked and large lakes created. The size of Swift Reservoir could be increased if a debris avalanche flowed down Swift Creek, overwhelmed the valley, and created a blockage taller than Swift Dam. At the east end of the reservoir, a debris avalanche moving down Pine Creek or Muddy River could cause blockage of the Lewis River.

The largest flood-surge-type lahar in the history of Mount St. Helens occurred in the Toutle River system about 2,500 years ago during the Pine Creek eruptive period. That lahar, which could perhaps serve as a worst-case example for the south side of the volcano, resulted from a lake breakout and had a volume of about 1 *billion* m³ after bulking (Scott, 1985b, in press). Catastrophic breaching of a natural dam, similar to that in the Toutle River system, has occurred at least once in the Lewis River valley during the volcano's 50,000-year history.

(3) Meltwater generated by a large pyroclastic flow. As a worst case, Crandell and Mullineaux (1978) computed the maximum probable size of a single lahar generated by a pyroclastic flow assumed to be similar in size to one that occurred on the south-southeast side of the volcano during the Pine Creek eruptive period. As discussed earlier, this estimate has been refined (toward a larger volume) based on more realistic values of snow density. On the basis of the bulking and debulking behavior of lahars preserved in the stratigraphic record, the pragmatic approach of Crandell and Mullineaux (1978) for estimating maximum probable size of a meltwater-generated lahar may be more technically valid than the approach of Cassidy and others (1980). Thus, for planning purposes, the largest single lahar generated by meltwater may be assumed to have a volume of about 170 million m³.

FUTURE ERUPTIVE PERIODICITY

During the past 4,500 years, the eruptive periods of Mount St. Helens generally have lasted less than a century and have been separated by dormant intervals lasting about 100 to 500 years (Crandell and Mullineaux, 1978, table 1). However, during the past 500 years, eruptive periods have occurred more frequently, with dormant intervals lasting only about 100 to 150 years (Crandell and Mullineaux, 1978, table 1). This time interval is well within the time span normally considered in long-range engineering and land-use decisions. Future behavior at similar intervals is highly probable, although the effect of the recent removal of such a vast part of the volcano is uncertain.

Given the near-certainty of another eruptive period, possibly within the lifetime of Swift Reservoir, the recurrence of a debris avalanche, a process that may have happened several times in the volcano's brief history, is the constraining design event in the Lewis River system. Although debris avalanches are less frequent than many other types of volcanic events, their enormous size and high velocity prevent them from being controlled by man-made structures. The only mitigation of such an event is evacuation of areas directly endangered (Schuster and Crandell, 1984).

REFERENCES CITED

- Beverage, J.P., and Culbertson, J.K., 1964, Hyperconcentrations of suspended sediment: Proceedings of American Society of Civil Engineers, Journal of the Hydraulics Division, v. 190, p. 117-128.
- Brantley, S.R., and Waite, R.B., in press, Interrelations among pyroclastic surge, pyroclastic flow, and lahars in Smith Creek valley during first minutes of 18 May 1980 eruption of Mount St. Helens, U.S.A.: Bulletin of Volcanology.
- Bretz, J.H., 1929, Valley deposits immediately east of the channeled scabland of Washington, I; II: Journal of Geology, v. 37, p. 393-427; p. 505-541.
- Cassidy, J.J., Coombs, H.A., and Shannon, W.L., 1980, Study of effects of potential volcanic activity on Lewis River projects: Portland, Oreg., Board of Consultants Report to Pacific Power and Light, 91 p.
- Chapin, C.E., and Elston, W.E., eds., 1979, Ash flow tuffs: Geological Society of America Special Paper 180, 211 p.
- Collins, B.D., and Dunne, T., 1986, Erosion of tephra from the 1980 eruption of Mount St. Helens: Geological Society of America Bulletin, v. 97, p. 896-905.
- Costa, J.E., and Schuster, R.L., 1987, The formation and failure of natural dams: U.S. Geological Survey Open-File Report 87-392, 39 p.
- Crandell, D.R., 1971, Postglacial lahars from Mount Rainier volcano, Washington: U.S. Geological Survey Professional Paper 677, 73 p.
- Crandell, D.R., and Mullineaux, D.R., 1973, Pine Creek volcanic assemblage at Mount St. Helens, Washington: U.S. Geological Survey Bulletin 1383-A, 23 p.
- 1978, Potential hazards from future eruptions of Mount St. Helens volcano, Washington: U.S. Geological Survey Bulletin 1383-C, 26 p.

- Crandell, D.R., Mullineaux, D.R., Rubin, M., Spiker, E., and Kelley, M.L., 1981, Radio-carbon dates from volcanic deposits at Mount St. Helens, Washington: U.S. Geological Survey Open-File Report 81-844, 15 p.
- Fairchild, L.H., 1987, The importance of lahar initiation processes, *in* Costa, J.E., and Wieczorek, G.F., eds., Debris flows/avalanches: Process, recognition, and mitigation: Geological Society of America Reviews in Engineering Geology, v. 7, p. 51-61.
- Fairchild, L.H., and Wigmosta, M., 1983, Dynamics and volumetric characteristics of the 18 May 1980 lahars on the Toutle River, Washington, *in* Symposium on Erosion Control in Volcanic Areas, Proceedings: Government of Japan, PWRI technical memorandum 1908, p. 131-154.
- Fisher, R.V., 1983, Flow transformation in sediment gravity flows: *Geology*, v. 11, p. 273-274.
- Fisher, R.V., and Schmincke, H.U., 1984, *Pyroclastic rocks*: New York, Springer-Verlag, 472 p.
- Glicken, H., 1986, Rockslide-debris avalanche of May 18, 1980, Mount St. Helens volcano, Washington: Santa Barbara, University of California, Ph.D. dissertation, 303 p.
- Hoblitt, R.P., Crandell, D.R., and Mullineaux, D.R., 1980, Mount St. Helens eruptive behavior during the past 1,500 years: *Geology*, v. 8, p. 555-559.
- Hopson, C.A., 1971, Eruptive sequence at Mount St. Helens, Washington [abs.]: Geological Society of America Abstracts with Programs, v. 3, no. 2, p. 138.
- Hyde, J.H., 1975, Upper Pleistocene pyroclastic-flow deposits and lahars south of Mount St. Helens volcano, Washington: U.S. Geological Survey Bulletin 1383-B, 20 p.
- Janda, R.J., Scott, K.M., Nolan, K.M., and Martinson, H.A., 1981, Lahar movement, effects, and deposits, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 461-478.
- Major, J.J., 1984, Geologic and rheologic characteristics of the May 18, 1980 southwest flank lahars at Mount St. Helens, Washington: University Park, Pa., The Pennsylvania State University, Master's paper, 225 p.
- Major, J.J., and Newhall, C.G., 1987, Effects of historical volcanic eruptions on snow and ice—a global review [abs.]: *Eos, Transactions of the American Geophysical Union*, v. 68, p. 1550.
- Major, J.J., and Voight, B., 1986, Sedimentology and clast orientations of the 18 May 1980 southwest flank lahars, Mount St. Helens, Washington: *Journal of Sedimentary Petrology*, v. 56, p. 691-705.
- Meyer, W., Sabol, M.A., Glicken, H.X., and Voight, B., 1985, The effects of ground water, slope stability, and seismic hazard on the stability of the South Fork Castle Creek blockage in the Mount St. Helens area, Washington: U.S. Geological Survey Professional Paper 1345, 42 p.
- Miller, C.D., Mullineaux, D.R., and Crandell, D.R., 1981, Hazards assessments at Mount St. Helens, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 789-802.
- Miller, D.J., 1960, Giant waves in Lituya Bay, Alaska: U.S. Geological Survey Professional Paper 354-C, p. 51-83.
- Mullineaux, D.R., 1986, Summary of pre-1980 tephra-fall deposits erupted from Mount St. Helens, Washington State, USA: *Bulletin of Volcanology*, v. 48, p. 17-26.
- Mullineaux, D.R., and Crandell, D.R., 1962, Recent lahars from Mount St. Helens, Washington: Geological Society of America Bulletin, v. 73, p. 855-870.
- 1981, The eruptive history of Mount St. Helens, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 3-15.
- Mullineaux, D.R., Hyde, J.H., and Rubin, M., 1975, Widespread late glacial and postglacial tephra deposits from Mount St. Helens volcano, Washington: U.S. Geological Survey Journal of Research, v. 3, p. 329-335.

- Mundorff, M.J., 1964, Geology and groundwater conditions of Clark County, Washington, with a description of the major alluvial aquifer along the Columbia River: U.S. Geological Survey Water-Supply Paper 1600, 268 p.
- 1984, Glaciation in the lower Lewis River basin, southwestern Cascade Range, Washington: Northwest Science, v. 58, p. 269–281.
- Newhall, C.G., 1982, A prehistoric debris avalanche from Mount St. Helens [abs.]: Eos, Transactions of the American Geophysical Union, v. 63, p. 1141.
- Noda, E., 1970, Water waves generated by landslides: Proceedings of American Society of Civil Engineers, Journal of Waterways and Harbors Division, v. 96, no. WW4, p. 835–855.
- Oltman, R.E., 1968, Reconnaissance investigations of the discharge and water quality of the Amazon River: U.S. Geological Survey Circular 552, 16 p.
- Osterkamp, W.R., Hupp, C.R., and Blodgett, J.C., 1986, Magnitude and frequency of debris flows, and areas of hazard on Mount Shasta, northern California: U.S. Geological Survey Professional Paper 1396–C, 21 p.
- Pierson, T.C., 1985, Initiation and flow behavior of the 1980 Pine Creek and Muddy River lahars, Mount St. Helens, Washington: Geological Society of America Bulletin, v. 96, p. 1056–1069.
- Pierson, T.C., and Scott, K.M., 1985, Downstream dilution of a lahar: transition from debris flow to hyperconcentrated streamflow: Water Resources Research, v. 21, p. 1511–1524.
- Portland General Electric Company, 1976, Trojan nuclear plant, final safety analysis report: Portland, Oreg., Portland General Electric Company Docket No. 50–344, v. 1, chap. 2, sec. 2.5, 47 p.
- Schuster, R.L., and Crandell, D.R., 1984, Catastrophic debris avalanches from volcanoes: International Symposium on Landslides, 4th, Toronto, Canada, v. 1, p. 567–572.
- Scott, K.M., 1985a, Lahars and flow transformations at Mount St. Helens, Washington, USA: International Symposium on Erosion, Debris Flow, and Disaster Prevention, Tsukuba, Japan, September 3–5, 1985, Proceedings, p. 209–214.
- 1985b, Lahars and lahar-runout flows in the Toutle-Cowlitz River system, Mount St. Helens, Washington—origin, behavior, and sedimentology: U.S. Geological Survey Open-File Report 85–500 (in press as Professional Paper 1447–A), 202 p.
- 1986, Lahars and lahar-runout flows in the Toutle-Cowlitz River system, Mount St. Helens, Washington—magnitude and frequency: U.S. Geological Survey Open-File Report 86–500 (in press as Professional Paper 1447–B), 120 p.
- in press, Origin, magnitude, and sedimentology of catastrophic lahars at Mount St. Helens, Washington, in Clifton, H.E., ed., Sedimentology of convulsive geologic events: Geological Society of America Special Paper.
- Scott, K.M., and Janda, R.J., 1987, Multiple origins of catastrophic lahars at Cascade Range volcanoes—probabilities of precursor events, and hazards in downstream areas [abs.]: Symposium on How Volcanoes Work, Hilo, Hawaii, January 19–25, 1987, p. 229.
- Scott, K.M., Janda, R.J., Major, J.J., Cameron, K.A., and Pringle, P., 1986, Assessment of lahar hazards at Cascade Range volcanoes from past flow histories [abs.], in Iverson, R.M., and Martinson, H.A., eds., American Geomorphological Field Group Annual Meeting Guidebook, Cispus Center, Wash., September 2–6, 1986, p. 170.
- Siebert, L., 1984, Large volcanic debris avalanches: characteristics of source areas, deposits, and associated eruptions: Journal of Volcanology and Geothermal Research, v. 22, p. 163–197.
- Slingerland, R.L., and Voight, B., 1979, Predictive models of landslide-generated water waves, in Voight, B., ed., Rockslides and avalanches 2—Engineering sites: New York, Elsevier, p. 317–397.
- Smith, G.A., 1986, Coarse-grained nonmarine volcanoclastic sediment: terminology and depositional process: Geological Society of America Bulletin, v. 97, p. 1–10.
- U.S. Army Corps of Engineers, 1984, Mount St. Helens, Washington feasibility report

- and environmental impact statement—Toutle, Cowlitz, and Columbia Rivers, v. 1.
- Verhoogen, J., 1937, Mount St. Helens, a recent Cascade volcano: California University Department of Geological Sciences Bulletin, v. 24, no. 9, p. 263–302.
- Voight, B., Glicken, H., Janda, R.J., and Douglass, P.M., 1981, Catastrophic rockslide avalanche of May 18, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens: U.S. Geological Survey Professional Paper 1250, p. 347–377.
- Voight, B., Janda, R.J., Glicken, H., and Douglass, P.M., 1983, Nature and mechanics of the Mount St. Helens rockslide-avalanche of 18 May 1980: *Geotechnique*, v. 33, p. 243–273.
- 1985, Nature and mechanics of the Mount St. Helens rockslide-avalanche of 18 May 1980, reply to discussion: *Geotechnique*, v. 35, p. 357–368.
- Waitt, R.B., 1980, About 40 last-glacial Lake Missoula jökulhlaups through southern Washington: *Journal of Geology*, v. 88, p. 653–679.
- 1984, Periodic jökulhlaups from Pleistocene glacial Lake Missoula—new evidence from varved sediment in northern Idaho and Washington: *Quaternary Research*, v. 22, p. 46–58.
- 1985, Case for periodic, colossal jökulhlaups from Pleistocene glacial Lake Missoula: *Geological Society of America Bulletin*, v. 96, p. 1271–1286.
- Waitt, R.B., Pierson, T.C., MacLeod, N.M., Janda, R.J., Voight, Barry, and Holcomb, R.T., 1983, Eruption-triggered avalanche, flood, and lahar at Mount St. Helens—effects of winter snowpack: *Science*, v. 221, p. 1394–1396.

Geology of Mount St. Helens Volcano, Washington

U.S. GEOLOGICAL SURVEY BULLETIN 1383

*This volume was published as
separate chapters A-D*



DEPARTMENT OF THE INTERIOR
DONALD PAUL HODEL, *Secretary*

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, *Director*

CONTENTS

[Letters designate the separately published chapters]

- (A) Pine Creek volcanic assemblage at Mount St. Helens, Washington, by Dwight R. Crandell and Donal R. Mullineaux.
- (B) Upper Pleistocene pyroclastic-flow deposits and lahars south of Mount St. Helens volcano, Washington, by Jack H. Hyde.
- (C) Potential hazards from future eruptions of Mount St. Helens volcano, Washington, by Dwight R. Crandell and Donal R. Mullineaux.
- (D) Volcaniclastic sedimentation in the Lewis River valley, Mount St. Helens, Washington, by Jon J. Major and Kevin M. Scott.

